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A comparative analysis of work-hour forecasting techniques at the crew level.

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A COMPARATIVE ANALYSIS OF WORK-HOUR FORECASTING TECHNIQUES AT THE CREW LEVEL

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A COMPARATIVE ANALYSIS OF WORK-HOUR FORECASTING TECHNIQUES AT THE CREW LEVEL

A Thesis in

Civil Engineering

by

James M. Pace

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ABSTRACT

Several different methods can be used to forecast the productivity of labor-intensive construction activities. The results from three widely used methods, percent complete, learning curve and standard productivity curve were used to test the practicality of a new forecasting method, the Factor Model, for a single masonry project. Forecasts were made at weekly intervals and then compared with the actual productivity at project completion. All of the methods produced divergent forecasts throughout the first third of the activity. However, the factor model produced a forecast within 4% of the final productivity after only 3% of the work had been completed.

While this research did not show that the factor model produced more accurate forecasts than the other methods, it did show that the forecasts were equally accurate. Thus, it appears that the factor model is a plausible alternative to conventional forecasting techniques.

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CHAPTER 1

INTRODUCTION

Forecasting is an integral part of the construction project control process that supports the highlighting of potential trouble areas, the taking corrective action, and the monitoring of the effectiveness of the actions taken. In the construction industry, there are several different forecasting methods available to predict activity duration and work-hour requirements.

Labor, materials and equipment are the major costs on a construction project. Typically, labor comprises 10 to 90 percent of the total project cost and is the most variable [1]. It follows that it is the most difficult cost to estimate and control [2]. This study analyzes different crew level forecasting methods.

PURPOSE OF RESEARCH

Several rudimentary forecasting methods have been available to contractors for many years. Typically, these methods assume that the utilization of resources will always follow some predefined standard pattern. These methods do not consider weather conditions, type of work, phase of the work, construction methods, design variables and crew size. Because these patterns are not determined uniquely for the work at hand, the forecasting accuracy using these methods can be very poor, especially during the early stages of the work.

The Factor Model of Construction Productivity, shown graphically

in Figure 1 [3], has been proposed to account for various job specific factors in order to improve crew level productivity forecasting, especially during the early stages of the work. Based upon this model concept, Sanders [4] derived 19 factors that affect crew level masonry productivity. However, the forecasting capabilities of this model have not been validated.

OBJECTIVE AND SCOPE

The objective of this thesis is to compare the labor productivity forecasting capabilities of the Factor Model to three other productivity forecasting methods. Weekly predictions for each method will be made for the masonry activity on a commercial construction project in State College, PA. The results of each method will be compared to the actual, total work-hours and how closely the different methods are able to model the actual progress of the work.

METHODOLOGY

The study is based on the following methodology.

Literature Review

To accomplish the stated objectives a systematic review of published material was done to identify information pertaining to construction productivity measurement and forecasting methods. The

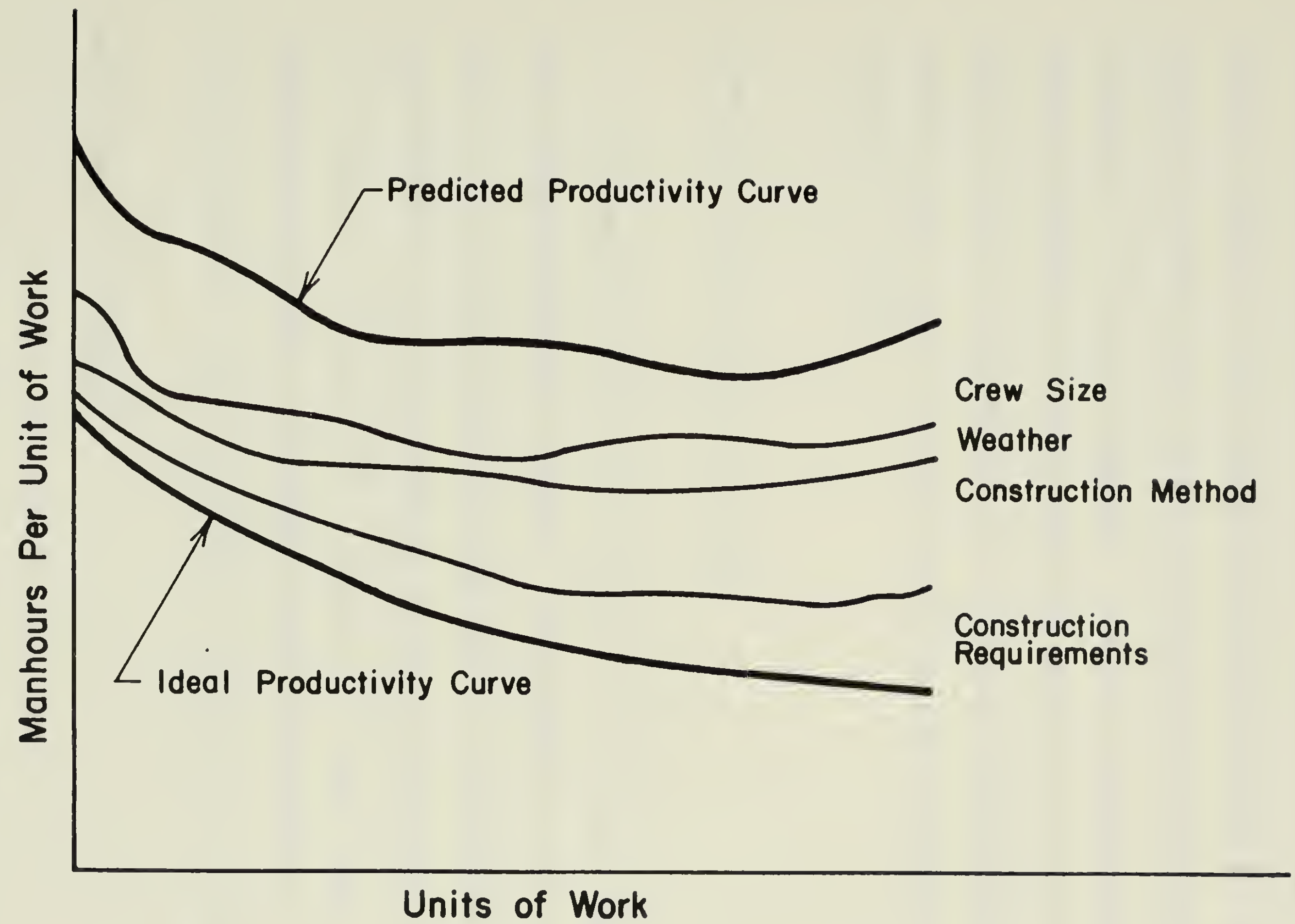

Figure 1. Factor Model

review began with information published by the Business Roundtable and the Construction Industry Institute. This was followed by a review of related research at The Pennsylvania State University. Other technical publications such as The Journal of Construction Engineering and Management, the Project Management Journal, and publications of the American Association of Cost Engineers were also reviewed. These various sources discussed several different forecasting methods and indicated that there is a need to develop more accurate crew level forecasting methods.

Selection of Project for Case Study

A commercial construction project in the State College, PA area was selected as the test project. The project was a four-story building built for the United Federal Savings Bank. The building is located near the intersection of South Atherton Street and University Drive and was built during the October 1988 to August 1989 time frame. It has a structural steel frame and masonry veneer construction. The contractor was the Leonard S. Fiore Construction Company, Inc., of Altoona, PA.

Development of Forecasts

Three forecasting methods were selected from the literature review. They were: Percent Complete, Learning Curve and Standard Productivity Curve. Forecasts for each method were developed prior to the start of the work. The quantity of masonry construction for the

various types of units and applications was also estimated from the contract documents. The cumulative productivity for each type of masonry unit and application was calculated based on the Factor Model concept. This information was also used to develop a milestone schedule that was consistent with the crew size planned by the contractor as well as a time-dependent predicted productivity curve for each forecasting method.

Data Collection

The project was visited daily, and production data, specifically work-hours, quantities, and other data, were collected in accordance with the "Procedures Manual for Collecting Productivity and Related Data of Labor-Intensive Activities on Commercial Construction Projects, Revision 2" [5].

Data Analysis

Forecasted productivity and total work-hours from each of the four methods were calculated at weekly intervals using the actual work-hours. The accuracy of the results using each method was evaluated in three ways. First, by equating how close each weekly productivity forecast compared with the final productivity. Second, a comparison of overall accuracy was made by summing the difference between each weekly forecast and the final productivity for each method. The third approach was to

compare the actual productivity trend with the predicted productivity trend curve for each method to determine which method best modeled what actually occurred on the project. Based upon these comparisons, a critique of the shortcomings of each method was made.

Expected Results

The research is expected to show that the various forecasting methods produce different results. The widest discrepancies are expected to be in the first phase of the activity. The research should provide valuable insight to support the development of better crew level forecasting capabilities.

Common terms

The following terms and definitions are used in this thesis.

Percent complete.--The percent complete of the masonry activity is calculated as the quantity measured in square feet divided by the total estimated quantity.

Labor productivity.-- Labor productivity is the work-hours divided by the quantity of masonry units installed. Smaller values show better productivity than do larger values. This is also referred to as the unit rate.

Standard masonry unit.-- Different sizes of masonry units require different levels of effort to install depending upon size and weight. Conversion factors are used to convert quantities of various sizes of units to an equivalent quantity of a standard unit. The standard unit is an 8 inch by 8 inch by 16 inch concrete masonry unit (c.m.u.) [4:64-66]. Conversion factors for lightweight concrete masonry units are based on the weight in pounds as follows:

$$\text{C.M.U. Conversion Factor} = 0.491 + 0.013(\text{Unit Weight}) \qquad (1)$$

The conversion factor for brick is based upon face area and using the following equation:

$$\text{Brick Conversion Factor} = 6.725 + 0.029(\text{Face Area}) - 1.837\ln(\text{Face Area}) \qquad (2)$$

All productivity values calculated in this report are expressed in terms of the equivalent quantities of the standard unit. Appendix A contains conversion factors for selected concrete masonry units and brick sizes.

Performance Factor.-- The performance factor is defined as:

$$\text{Performance Factor (P.F.)} = \frac{\text{Planned Unit Rate}}{\text{Actual Unit Rate}} \qquad (3)$$

Report Outline

The report will generally follow the methodology previously described. Chapter 2 discusses the various crew level forecasting methods, how they are derived, predicted productivity curves, how to develop a forecast and cites other methods reported in the literature review. Chapter 3 details the process of developing a forecast based on the Factor Model. This process is then used to develop a forecast for the case study project. Chapter 4 explains the actual progress of the case study project and describes unique situations that occurred during construction. Chapter 5 compares the actual productivity to the forecasts developed for the four methods. Chapter 6 outlines the conclusions and recommendations for future work.

CHAPTER 2

METHODS OF CREW LEVEL FORECASTING

Several methods are recognized for forecasting crew level labor productivity. These are listed in Table 1. The assumptions and limitations of each method are listed as well as the information required to develop a forecast. The methods are: percent complete, learning curve, standard productivity curve and the Factor Model.

This chapter describes the various methods of crew level forecasting.

OVERVIEW OF ACCEPTED FORECASTING METHODS

The accepted forecasting methods: percent complete, learning curve and the standard productivity curve are described in the following section. The proceedure for developing a labor forecast for each method is illustrated using the sample data in Table 2.

Percent Complete Method

The percent complete method of forecasting is the simplest and most commonly used forecasting method. The forecasted work-hours at completion are computed by dividing the work-hours expended to date by the percent complete of the activity as shown in the following equation [2:77]:

Table 1. - Forecasting Methods

Method	Assumptions	Comments	Information Required
Percent Complete	Predicted productivity remains unchanged until the end of the activity. Forecast is a function of to date performance and ignores factors affecting productivity.	Large errors occur where productivity is highly variable	Percent Complete and work-hours to date
Learning Curve	Productivity follows predefined pattern of continuous improvement. The forecast is a function of learning rates defined for broad categories of work and ignores factors affecting productivity. The trend for every job is the same and differs only by the rate of improvement.	Forecast does not consider changes in work content or construction sequencing and method, i.e., does the contractor do the hard or easy work first. Accuracy is dependent on the uniformity of the work throughout the duration. Variations in difficulty can yield unreliable results.	Total est. quantity, estimated cumulative productivity at completion

(cont. on next page)

Table 1. (cont.)

Method	Assumptions	Comments	Information Required
Standard Productivity Curve	Assumes that there will be changes in productivity during different phases, i.e., start-up, production, finish work. Model assumes that every project proceeds in the same way.	Most applicable on large projects for bulk installations. Multiple crews give an average productivity trend but trends of individual crews can be very different from the standard curve.	Total est. quantity, estimated cumulative productivity at completion, standard productivity curve

(cont. on next page)

Table 1. (cont.)

Method	Assumptions	Comments	Information Required
Factor Model	Assumes that construction methods, site management, weather, type of work, phase of work, design variables and crew size yield different productivities and the effect of these factors can be quantified. A unique trend curve is derived for each activity. Can be inaccurate unless all significant factors affecting productivity are considered.	More detailed calculations must be integrated with a milestone schedule describing the sequencing of major elements of the work.	Total est. quantity, design features, crew size, expected weather, type of work, phase of work, milestone schedule

Table 2. - Sample Project Summary

	Estimated	To Date (3 Weeks)
Quantities (sq.ft.)	37,728	2,243
Work-hours	6,813	407
Cumulative Productivity (wh/sq.ft.)	0.181	0.181
Duration (weeks)	27	-
Percent Complete	-	5.9

$$\text{Work-hours Forecast at Completion} = \frac{\text{Total Estimated Quantities}}{\text{Quantities to Date}} \times \text{Work-hours to Date} \qquad (4)$$

The forecast work-hours at completion are then divided by the total quantity estimate to obtain the forecast unit rate at completion.

Figure 2 shows the forecasted productivity for the sample data. Notice that the percent complete method assumes that productivity will be constant through out the entire activity. Significant forecasting errors can result if the cumulative unit rate changes. Table 3 shows a hypothetical forecast at the end of the third week.

Learning Curve

In theory, productivity should improve as the crew becomes more familiar with the work. A straight line learning curve assumes that the improvement declines at a constant rate as the number of repetitions

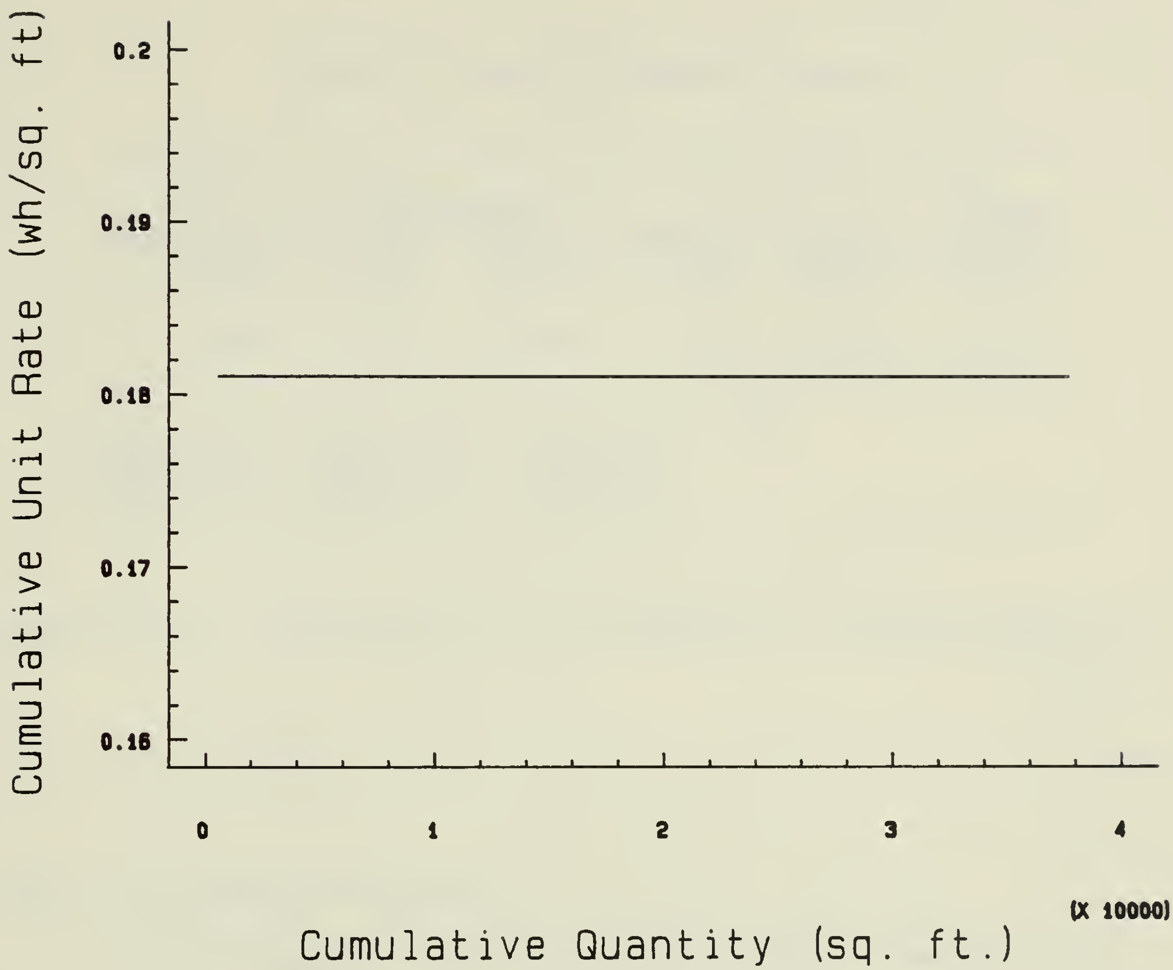

Figure 2. Productivity Trend Curve Based on Percent Complete Method

Table 3. - Percent Complete Forecast

	Work-hours					Percent
Week	Budgeted (1)	To Date (2)	Forecast (3)	Overrun (4)	Variance (5)	Complete (6)
3	6813	407	6898	85	1.01	5.9

Column (3) = Column (2) - Column (6) x 100
Column (4) = Column (3) - Column (1)
Column (5) = Column (3) - Column (1)

double [6:21]. The equation for the straight line learning curve is:

$$Y = A\ X^{-n} \tag{5}$$

where Y = cumulative unit rate

A = the number of work-hours needed to complete the first unit

X = unit or sequence number

n = slope of the logarithmic curve

The slope of the curve (n) is based on an assumed learning rate. Common learning rates and slopes are given in Table 4. When plotted using log-log scale, Equation 5 is a straight line.

Table 5 lists typical learning rates presented by Gates and Scarpa for the construction industry [7]. Daytner found that the learning rate for several masonry projects varied from 85% to 96% [8:50]. Based upon these data, a learning rate of 90% was selected for the sample project. Using the estimated quantity and productivity at completion from Table

Table 4. - Learning Rates and Corresponding Slopes

Learning Rate (%)	70	75	80	85	90	100
Slope n	0.515	0.415	0.322	0.234	0.152	0.000

Source: Ward, 1984

Table 5. - Learning Rates for Repetitive Construction Activities

	Description	Learning Rate
1.	Entire structure of ordinary complexity such as high-rise office buildings and tract housing	95%
2.	Individual construction elements requiring <u>many operations to complete</u> such as carpentry, electrical work, plumbing, erection and fastening of structural units, concreting	90%
3.	Individual construction elements requiring <u>few operations to complete</u> such as masonry, floor and ceiling tile, painting	85%
4.	Construction elements requiring <u>few operations on an assembly-line basis</u> such as field fabrication of trusses, formwork panels and bar bending	80%
5.	<u>Plant manufacture</u> of building elements such as doors, kitchen cabinets, and prefabricated concrete panels	90 - 95%

Source: Gates and Scarpa, 1972

2, the value of (A) can be computed using Equation 5. This is shown below.

$$0.181 = A \times (37{,}720)^{-0.152}$$

$$A = 0.898$$

It follows that the equation for the straight line learning curve for the example project is:

$$Y = 0.898 * X^{-0.152} \qquad (6)$$

Equation 6 was used to plot the cumulative productivity predictions shown in Figure 3.

Next a forecast of the final work-hours was made at the end of week three using the following equation:

$$\begin{matrix}\text{Forecast}\\ \text{Work-hours}\end{matrix} = \left[\begin{matrix}\text{Actual}\\ \text{To Date}\\ \text{Unit}\\ \text{Rate}\end{matrix} - \begin{matrix}\text{Predicted}\\ \text{To Date}\\ \text{Unit}\\ \text{Rate}\end{matrix} + \begin{matrix}\text{Estimated}\\ \text{Final}\\ \text{Unit}\\ \text{Rate}\end{matrix}\right] \times \begin{matrix}\text{Current}\\ \text{Quantity}\\ \text{Estimate}\end{matrix} \qquad (7)$$

$$= (0.181 - 0.278 + 0.181) \times (37{,}720) = 3{,}168 \text{ work-hours}$$

The predicted to date unit rate is computed using Equation 6. Equation 7 computes the distance between the predicted productivity trend curve and the actual curve. It assumes that the distance between the actual productivity curve and the predicted curve will be the same throughout the activity´s duration. As can be seen this forecast is

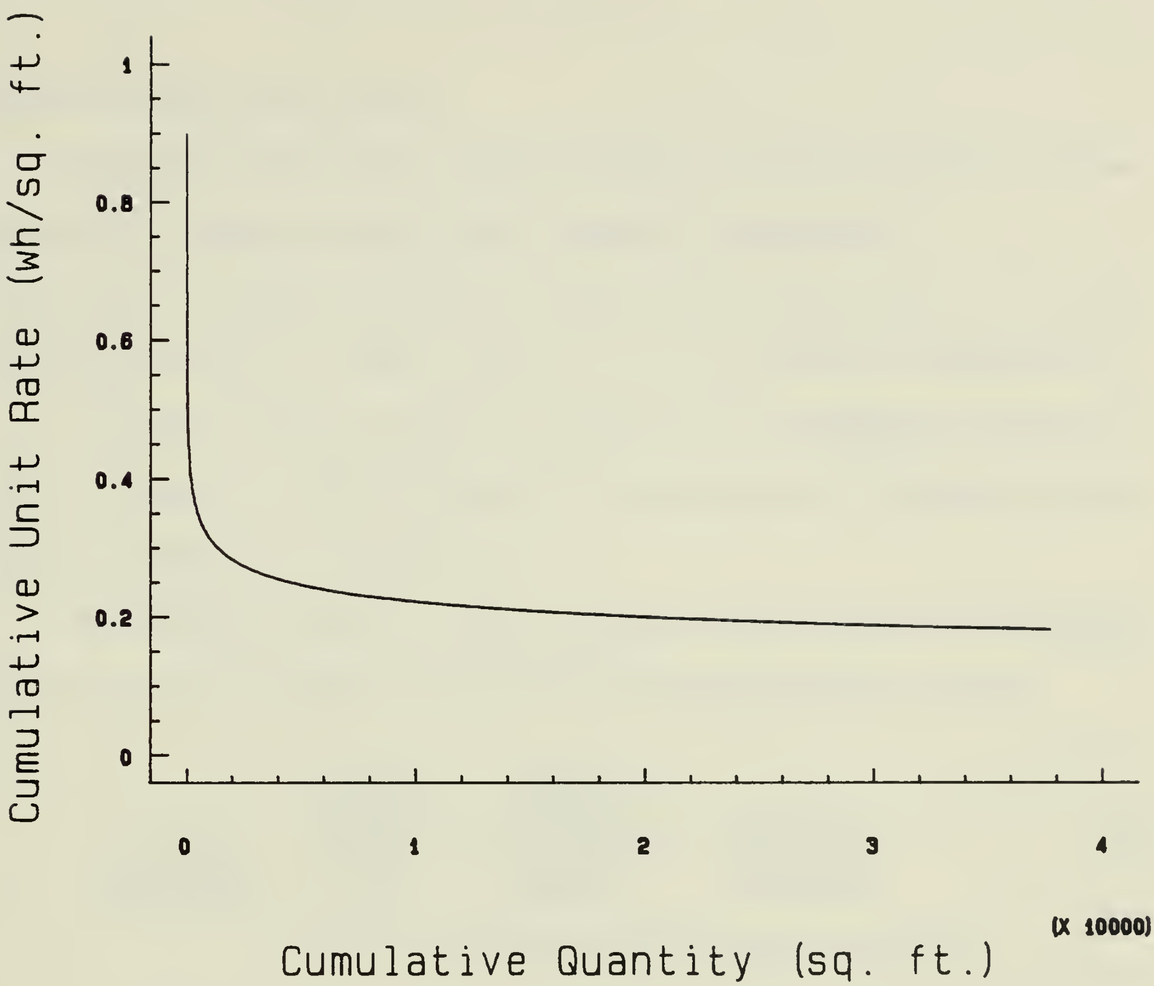

Figure 3. Learning Curve for Masonry Based on 90% Learning Rate

very different from the percent complete method.

Standard Productivity Curves

Standard productivity curves are based on past experiences of how productivity changes during a bulk commodity installation. Historically, standard productivity curves have been applied to the work of multiple crews on a large project, not to the work of a single crew.

A typical curve for masonry construction on commercial projects is shown in Figure 4. Crew performance is expressed as a function of the percent complete of the activity.

The standard curve was used to forecast work-hours for the sample data at the end of week three with the following equation [2:87]:

$$\begin{array}{c} \text{Forecast} \\ \text{Work-hours} \end{array} = \begin{array}{c} \text{Actual} \\ \text{To Date} \\ \text{Unit} \\ \text{Rate} \end{array} \times \begin{array}{c} \text{Expected} \\ \text{To Date} \\ \text{Performance} \\ \text{Factor} \end{array} \times \begin{array}{c} \text{Current} \\ \text{Quantity} \\ \text{Estimate} \end{array} \qquad (8)$$

$$= 0.181 \times 0.74 \times 37{,}720 = 5{,}052 \text{ work-hours}$$

The result using this method is different from the forecasts for the percent complete and learning curve.

FACTOR MODEL

The Factor Model is based upon research conducted at The Pennsylvania State University. It theorizes that the work of the crew is affected by various factors that may lead to random and systematic disturbances in the work. The cumulative effect of these disturbances

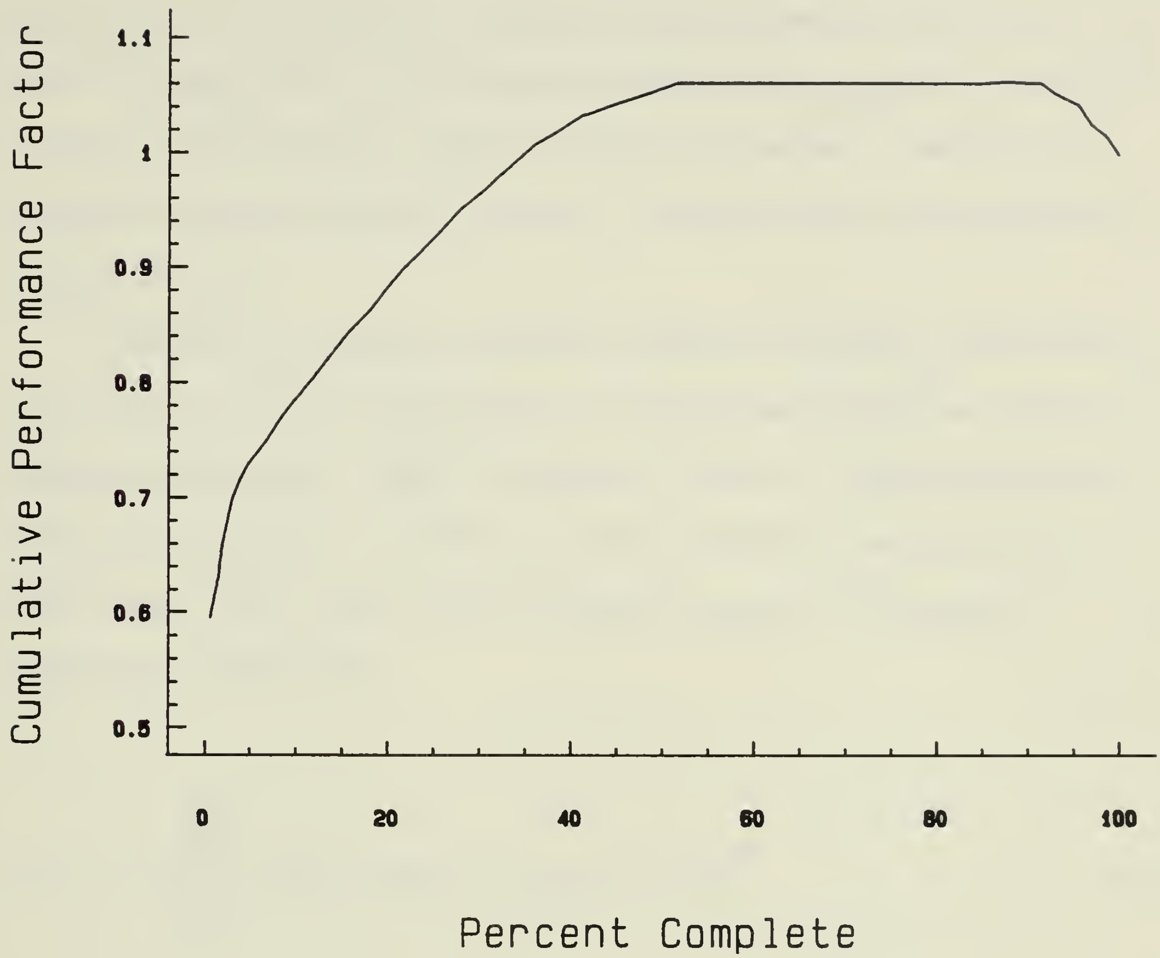

Figure 4. Standard Productivity Curve for Masonry

yields an actual productivity curve. The disturbances can be mathematically discounted to produce an ideal productivity curve. The shape and magnitude of the predicted productivity curve is a function of a number of factors that reflect the site environment, construction methods and constructability aspects. The model was shown graphically in Figure 1 [3].

Sanders [4] conducted extensive research on masonry construction activities in Central Pennsylvania and identified 19 factors affecting masonry productivity. These are shown in Table 6. Using multivariant statistical analyses, the effect of these variables was quantified. These values can be used in the following equation to develop a productivity prediction:

$$E(P) = b_0 + \sum_{i=1}^{n-3} b_i x_i + b_{n-2} cs + b_{n-1} cs^2 + b_n cs^3 \tag{9}$$

where $E(P)$ = expected productivity

b_0 = constant term defining the base unit rate

$b_i, \ldots, b_{n-3}$ = model coefficients showing how much productivity changes when factor x_i is present

x_i = an indicator variable representing the presence of a factor known to affect productivity

cs = crew size

n = number of terms in the model

Using the predictions for the various phases and types of work and a

Table 6. - Factor Model Factors

Base Unit	0.04732

Adjustment Factors

Work Type

Variable	Adjustment
Repetitive 1st Floor	-0.0111
Repetitive Other	-0.0291
Brick	0.0047
Other	-

Work Phase

Variable	Adjustment
Foundation	-
Exterior Walls	0.0083
Interior Straight Walls	0.0244
Interior Core Walls	0.0555
Column/Ornamental	0.0078
Penthouse	0.0389
Finish Work	0.1478

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Table 6. (cont.)

Design Details	
Variable	Adjustment
None	-
Cutting	0.0287
Restricted Access	0.0614
Quality Control Requirements	0.0161
Double-wythe	-0.0139
Straight Walls	-0.0315
Block and Brick	0.0003

Weather	
Variable	Adjustment
Low Temp, Low Humidity	-0.0196
Medium Temp, Low Humidity	-0.0019
High Temp, Low Humidity	0.0101
Low Temp, Medium Humidity	-0.0223
Medium Temp, Medium Humidity	-
High Temp, Medium Humidity	0.0056
Low Temp, High Humidity	-0.0246
Medium Temp, High Humidity	-0.0016
High Temp, High Humidity	0.0093

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Table 6. (cont.)

Crew Size	
Variable	Adjustment
Crew Size	0.0142
Crew Size Squared	-0.0011
Crew Size Cubed	0.000027

milestone schedule, a predicted productivity trend curve can be developed. Chapter 3 will detail this process for the case study project. Using this trend curve, productivity forecasts can be calculated using Equation 7.

OTHER FORECASTING MODELS

Based on published literature, there is general agreement that crew level forecasting models need to be improved [1,9,10]. The literature search indicated that most approaches focus on forecasting trends for an entire project [11,12,13], a geographical area [1], or describe variations of existing forecasting methods [10,14]. Several construction manuals were consulted. While these acknowledged that good forecasting was essential to a successful project, they did not explain how forecasts should be done [15,16,17]. Thus, it appears that the three forecasting techniques described in this chapter are the only ones that have been applied in the construction industry.

SUMMARY

This chapter provides an overview of the four different forecasting methods that will be used in this study. The percent complete, learning curve and standard productivity curve methods are based on generalized standards of performance and produce different results when used to forecast for the same activity. The Factor Model accounts for specific job factors such as work phase, design details and work method. It requires a milestone schedule to develop a forecast.

CHAPTER 3

DEVELOPING FACTOR MODEL

FORECAST FOR CASE STUDY

This chapter describes the case study project and details the development of a productivity trend curve based on the Factor Model.

PROJECT DESCRIPTION

A commercial construction project in the State College area was selected for this study. The contractor, Leonard S. Fiore, Inc., granted permission to monitor the daily productivity and collect other information necessary to evaluate the productivity of the masonry construction.

Type of Project

The case study project is the United Federal Bank Building. It is a four-story structure and consists of a structural steel frame and masonry veneer facade. The building is located near the intersection of South Atherton Street and University Drive. Table 7 summarizes relevant information about the project. Photographs showing the unique design of the building are shown in Figures 5 and 6. The construction included irregular corners as can be seen in the first floor plan, Figure 7. The floor plans for the remaining floors are included in Appendix B.

Table 7. - United Federal Bank Summary Statistics

Location	State College, PA
Project cost ($ million)	2.2
Type of structural frame	Structural steel
No. of stories	4
Building height (ft.)	55
First floor plan area (sq. ft.)	8,132
Site area (sq. ft.)	44,705
Building to site area ratio	0.18
Responsible entity	General Contractor
No. of workdays required	110
Average crew size	10
Labor force	Nonunion
Actual square feet of masonry	37,440
Work-hours required	8,881
Cumulative productivity (wh/sqft)	0.237
Construction time frame	Oct.-June

Figure 5. South View of Completed United Federal Bank

Figure 6. North View of Completed United Federal Bank

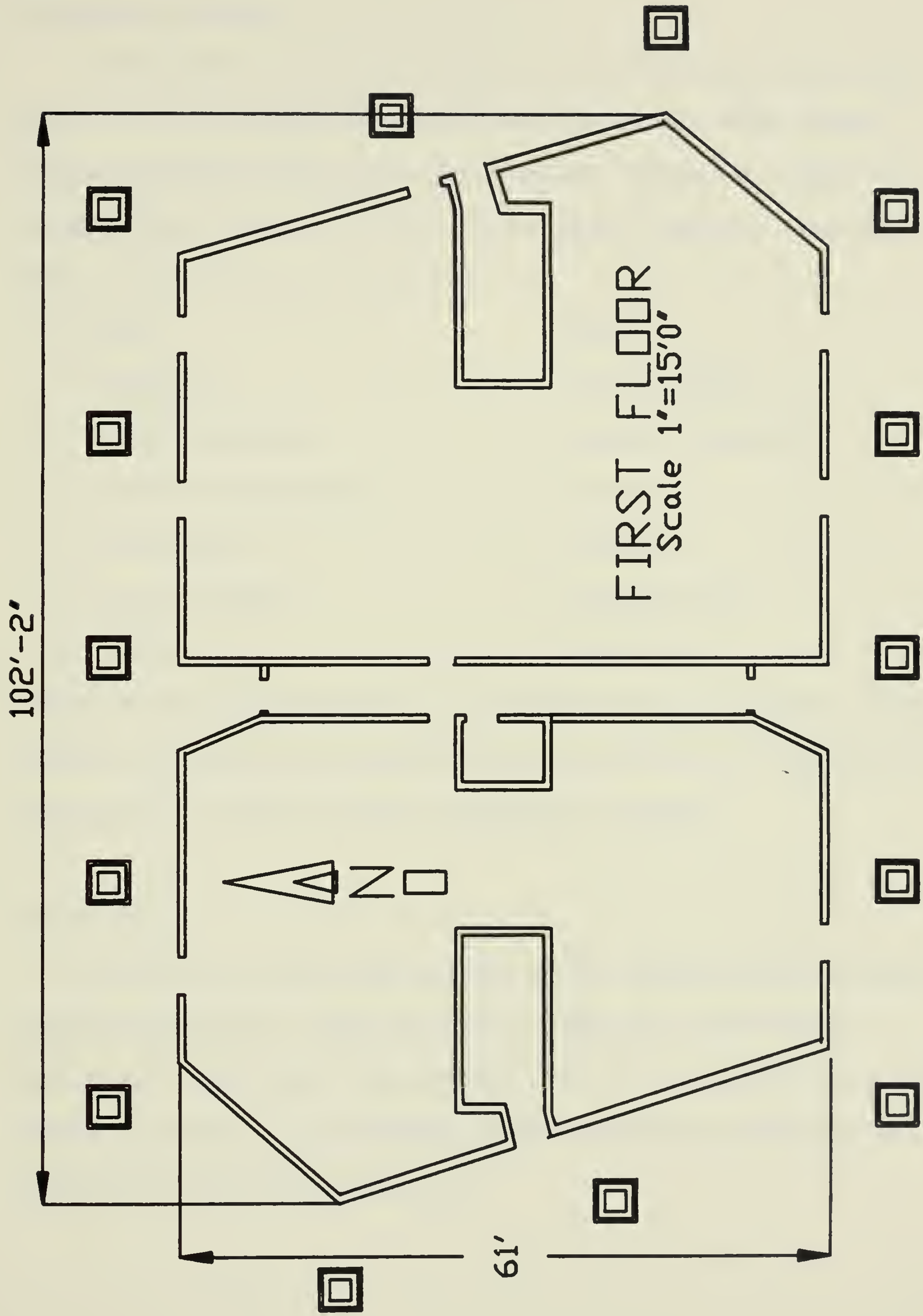

Figure 7. First Floor Plan of United Federal Bank

Uniqueness of Design

This project is uniquely suited to test the Factor Model theory because of the wide range of architectural features. These include concrete block and triple-wythe brick walls of different lengths and configurations. Of the 19 different parameters that were listed in Table 6, the following 14 were used:

Brick	Other
Foundation	Exterior Walls
Column/Ornamental	Interior Core Wall
Interior Straight Wall	Finish
Double-Wythe	Cutting
Block and Brick	Straight Walls
Weather	Crew Size

Because of the unique design of the building with its irregular corners, numerous core walls, and cutting of block and brick, the difficulty of developing an accurate forecast was greatly increased.

Time of Year

The project posed unique construction problems because the owner wanted construction to begin as soon as possible. To meet this requirement, construction was scheduled to begin in October and proceed through the winter. This schedule also increased the difficulty of accurately forecasting productivity.

FACTOR MODEL PRODUCTIVITY TREND CURVE

To develop a predicted productivity curve base on the Factor Model, the steps outlined in Figure 8 were applied to the case study. These are explained below.

Partition Work by Line Item

The initial step in developing a trend curve is to partition the work into line items according to work type, work phase, design detail, expected weather and planned crew size (see Table 6). A line item is a division or item of work for which there is a single identifying category for work type, work phase, and design detail. For example, the line item stairwells can be uniquely described as: other; interior core wall; cutting. The criteria for the work type, work phase and design detail are contained in Appendix C.

Quantity Takeoff

A detailed quantity estimate was made by first dividing the masonry activity into 18 different line items. The surface area for each line item, except for temporary enclosures for protection during the winter months, was then determined from the project drawings. The unit of measure is square feet of wall area, etc., excluding windows and doors.

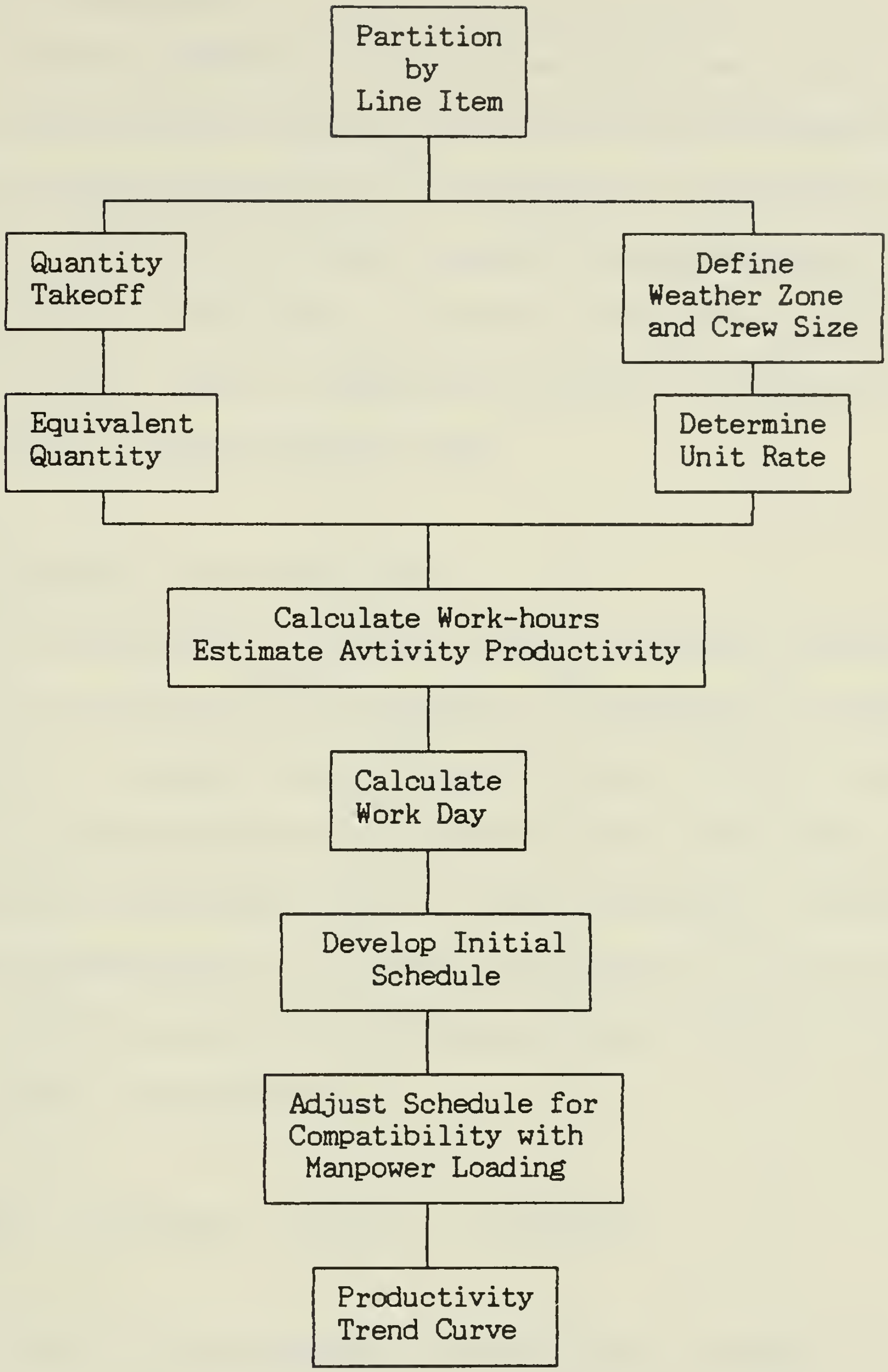

Figure 8. Flow Chart for Using Factor Model

Equivalent Quantities

Once the quantity estimate for each line item of work is obtained, the estimated quantity needs to be converted into equivalent quantities of the standard masonry unit. The standard is a lightweight 8" x 16" x 8" c.m.u. The total equivalent quantity of standard masonry units for the activity is calculated as the sum of the equivalent quantities for each line item. Table 8 summarizes the quantity estimates and the conversion to standard masonry units.

Define Weather Zone and Crew Size

The adjustments for weather effects developed by Sanders are based on various zones of relative humidity and temperature as shown in Figure 9 [4:110]. A single zone is selected for each line item. Based on the masonry specifications for the project and the time of year when construction was planned, zone 5, with no adjustment, was selected as being representative of the weather conditions for the all line items.

Sanders proposed the following polynomial equation to account for differences in crew size [4]:

$$f(cs) = 0.0142cs - 0.0011cs^2 + 0.000027cs^3 \qquad (10)$$

where f(cs) is the adjustment to the base unit rate and cs is the planned crew size.

A crew size is determined for each item. The contractor planned to use three different crew sizes, a four person crew during mobilization, start up and for the foundations, a 15 person crew during

Table 8. - Summary of Quantity Estimates and Conversion to Standard Units

Line Item	Masonry Type and Size	Conversion Factor (1)	Estimated Quantities Measured (sq. ft.) (2)	Standard Unit (sq. ft.) (3)
Foundation	C.M.U. 16"x8"x8"	1.02	34	35
Foundation	Brick 8"x4"x3"	1.73	533	922
Perimeter Walls	Brick 8"x4"x3"	1.73	696	1,204
Exterior Walls Phase 1	C.M.U. 16"x8"x8"	1.02	1,150	1,173
Exterior Walls Phase 2	C.M.U. 16"x8"x8"	1.02	600	612
Columns	C.M.U. 16"x8"x8"	1.02	1,500	1,530
Columns	Brick 8"x4"x3"	1.73	1,677	2,901
Elevator Phase 1	Brick 8"x4"x3"	1.73	1,523	2,634
Elevator Phase 2	Brick 8"x4"x3"	1.73	1,197	2,070
Stairwells Phase 1	Brick 8"x4"x3"	1.73	4,476	7,743
Stairwells Phase 2	Brick 8"x4"x3"	1.73	4,322	7,477
Vestibule	Brick 8"x4"x3"	1.73	215	372
Stairwell End Wall	Brick 8"x4"x3"	1.73	1,448	2,505
Divider Walls Phase 1	Brick 8"x4"x3"	1.73	1,954	3,380
Divider Walls Phase 2	Brick 8"x4"x3"	1.73	1,487	2,572
Single-wythe	Brick 8"x4"x3"	1.73	114	197
Finish	Brick 8"x4"x3"	1.73	225	389
Total Quantities			23,151	37,720

Column (3) = column (1) x column (2)

Relative Humidity, RH	$T<40$	$40 \le T \le 80$	$T>80$
$RH>80$	Zone 7 -0.0246	Zone 8 -0.0016	Zone 9 0.0093
$40 \le RH \le 80$	Zone 4 -0.0223	Zone 5 -	Zone 6 0.0056
$RH<40$	Zone 1 -0.0196	Zone 2 -0.0019	Zone 3 0.0101

Temperature, T ($^{\circ}$F)

Figure 9. Weather Zones

the major portion of the work, and a six person crew during the final portion of the project. Using a crew size of 15 , Equation 10 yields the following adjustment:

$$f(cs) = 0.0142(15) - 0.0011(15^2) + 0.000027(15^3)$$

$$f(cs) = 0.0213 - 0.2475 + 0.0911$$

$$f(cs) = 0.0566$$

Determine Unit Rate

The predicted unit rate for each line item is calculated using Equation 9. This equation is the summation of the base unit rate and the adjustment factors for work type, work phase, design details, weather and crew size (see in Table 6).

Table 9 relates the Factor Model coefficients in Table 6 to the line items in Table 8. Equation 9 was used to calculate the predicted unit rate for each line item.

For the exterior c.m.u. wall, phase 1, the predicted unit rate is:

base unit	0.0473
work type - other	0.0000
work phase - exterior walls	0.0083
design details - cutting	0.0287
weather - zone 5	0.0000
crew size - 15	0.0566
Predicted unit rate	0.1409

Predicted unit rates for each line item are summarized in Table 10.

Table 9. - Factor Model Coefficients for Each Line Item

Line Item	Base Unit Rate	Work Type	Work Phase	Design Details	Weather	Crew Size	Crew Factor
Foundation C.M.U.	0.0473	0.0000	0.0000	0.0000	0.0000	4	0.0409
Foundation Brick	0.0473	0.0047	0.0000	-0.0139	0.0000	4	0.0409
Perimeter	0.0473	0.0047	0.0083	-0.0139	0.0000	15	0.0566
Exterior Walls I	0.0473	0.0000	0.0083	0.0287	0.0000	15	0.0566
Exterior Walls II	0.0473	0.0000	0.0083	0.0287	0.0000	15	0.0566
Columns C.M.U.	0.0473	0.0000	0.0078	0.0003	0.0000	6	0.0514
Columns Brick	0.0473	0.0047	0.0078	0.0003	0.0000	6	0.0514
Elevator Phase I	0.0473	0.0047	0.0555	-0.0139	0.0000	15	0.0566
Elevator Phase II	0.0473	0.0047	0.0555	-0.0139	0.0000	15	0.0566
Stairwells Phase I	0.0473	0.0047	0.0555	0.0287	0.0000	15	0.0566
Stairwells Phase II	0.0473	0.0047	0.0555	0.0287	0.0000	15	0.0566
Stairwells End Wall	0.0473	0.0047	0.0555	0.0287	0.0000	15	0.0566
Vestibule	0.0473	0.0047	0.0555	0.0287	0.0000	15	0.0566
Divider I	0.0473	0.0047	0.0555	0.0287	0.0000	15	0.0566
Divider II	0.0473	0.0047	0.0555	0.0287	0.0000	15	0.0566
Single-wythe	0.0473	0.0047	0.0244	-0.0315	0.0000	15	0.0566
Finish	0.0473	0.0000	0.1478	0.0000	0.0000	6	0.0514
Temporary Enclosure	0.0000	0.0000	0.0000	0.0000	0.0000		0.0000

Table 10. - Predicted Unit Rates

Line Item	Expected Unit Rate
Foundation C.M.U.	0.088
Foundation Brick	0.079
Perimeter	0.103
Exterior Walls I	0.141
Exterior Walls II	0.141
Columns C.M.U.	0.107
Columns Brick	0.112
Elevator Phase I	0.150
Elevator Phase II	0.150
Stairwells Phase I	0.193
Stairwells Phase II	0.193
Stairwells End Wall	0.193
Vestibule	0.193
Divider I	0.193
Divider II	0.193
Single-wythe	0.102
Finish	0.247
Temporary Enclosure	0.000

Calculate Work-hours, Estimate Productivity

The work-hours required to complete each line item are calculated by multiplying the line item unit rate by the equivalent quantity of standard masonry units. Appendix D contains a comparison of estimates for the case study made using the Factor Model and Richardson´s Estimating System.

Table 11 summarizes the durations for each line item. For example, the work-hours for the exterior c.m.u. wall, phase 1 are:

Work-hours = Predicted Unit Rate x Equivalent Quantity

Work-hours = 0.1409 x 1,173 = 165

An additional line item, totaling 412 work-hours, was also added for the construction and relocation of temporary enclosures for cold weather protection.

The total work-hours for the activity are calculated the as the sum of the work-hours for each line item. The total work-hours are then divided by the total quantity of standard masonry units to determine the estimated cumulative productivity rate for the activity.

Calculate Work Days

Once the predicted unit rate and work-hours were determined for each line item, the work-hours and work days were calculated. An eight hour work day was assumed for the duration of the activity. The duration in work days is for the exterior c.m.u. wall, phase 1 is:

Work Days = Work-hours - (Crew Size x Length of Work Day)

Work Days = 165 - (15 x 8) = 1.4

This information is also summarized in Table 11. As can be seen, the

Table 11. - Summary of Work-hours and Work Days

Line Item	Expected Unit Rate (1)	Standard Unit Quantity (sq. ft.) (2)	Work Hours (3)	Work Days (4)
Foundation C.M.U.	0.088	35	3	0.1
Foundation Brick	0.079	922	73	2.3
Perimeter	0.103	1204	124	1.0
Exterior Walls I	0.141	1173	166	1.4
Exterior WallsII	0.141	612	86	0.7
Columns C.M.U.	0.107	1530	165	3.4
Columns Brick	0.112	2901	324	6.7
Elevator Phase I	0.150	2635	396	3.3
Elevator Phase II	0.150	2071	311	2.6
Stairwells Phase I	0.193	7743	1493	12.4
Stairwells Phase II	0.193	7477	1442	12.0
Stairwells End Wall	0.193	372	72	0.6
Vestibule	0.193	2505	483	4.0
Divider I	0.193	3380	652	5.4
Divider II	0.193	2573	496	4.1
Single-wythe	0.102	197	20	0.2
Finish	0.247	389	96	2.0
Temporary Enclosure	-	0	412	3.4
TOTALS		37720	6813	65.8

Column (3) = column (1) x column (2)
Column (4) = column (3) - planned daily work-hours

stairwells are the most time consuming items in the activity.

Develop Initial Schedule

Once the required work days for each line item are determined, the initial schedule for the activity is developed. The masonry schedule was developed based on the duration of each line item and their logical sequencing. The schedule for the case study was divided into three phases: the start-up of work consisting of the foundations, the production phase, and the finishing phase consisting of the columns and finish work. The initial schedule with a planned duration of 66 work days is shown in Figure 10 along with the projected daily work-hour loading. This is based on a crew size of 4 for the start-up phase, 15 for the production phase and 6 for the finishing phase.

Adjust Schedule

The initial schedule was revised by extending the duration of concurrent line items so that they could be accomplished within the available daily work-hour limits and in the proper sequence. On these days the available work-hours are divided between the scheduled line items, and their durations are extended to account for the reduced output. Figure 11 is the revised schedule. The total planned duration of 66 work days remained the same as originally scheduled.

Once the revised schedule was developed, the daily unit rate was determined. On days when several activities were in progress, a weighted average daily productivity was calculated. Table 12 contains a summary of the predicted productivity for each work day.

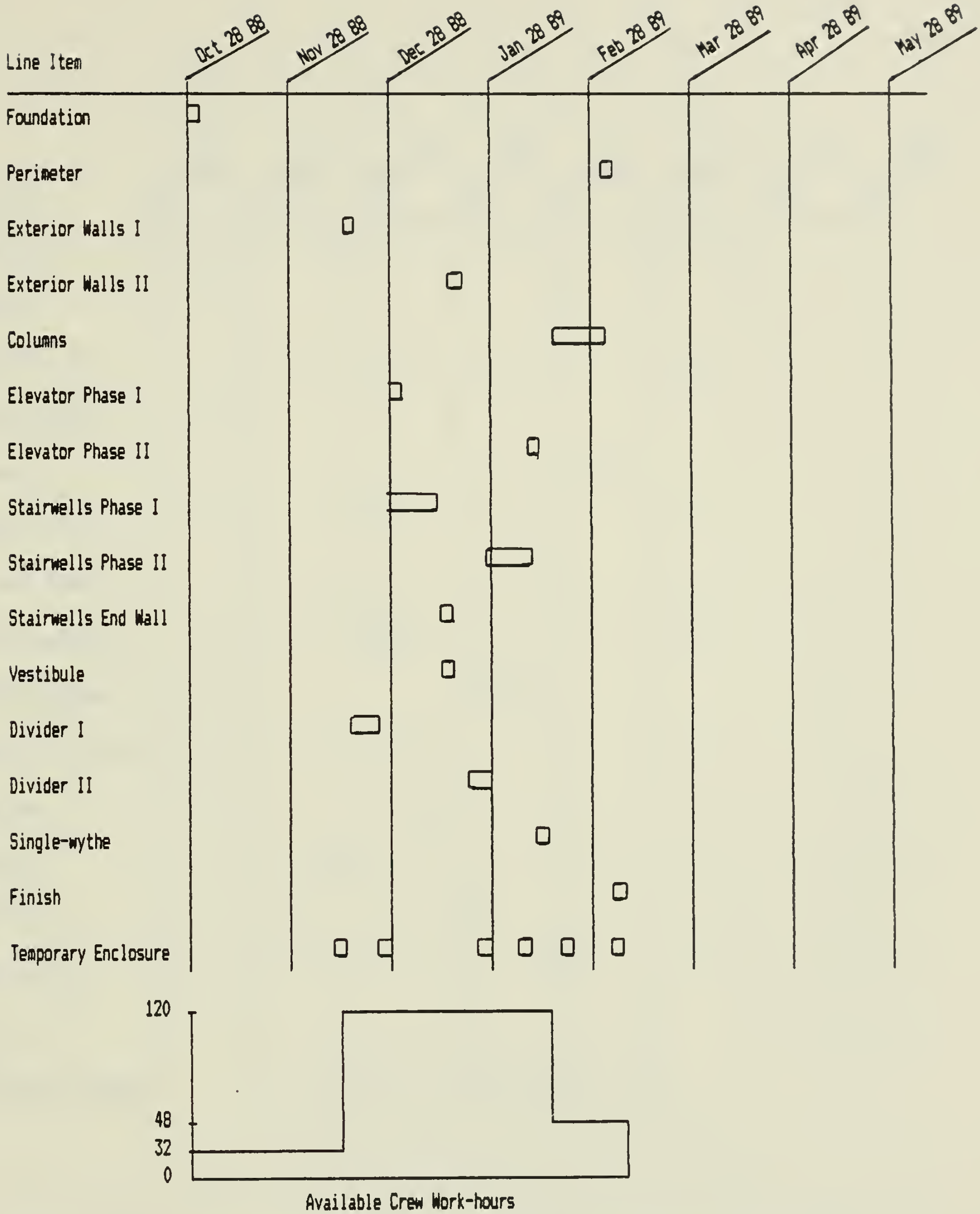

Figure 10. Initial Masonry Schedule for United Federal Bank

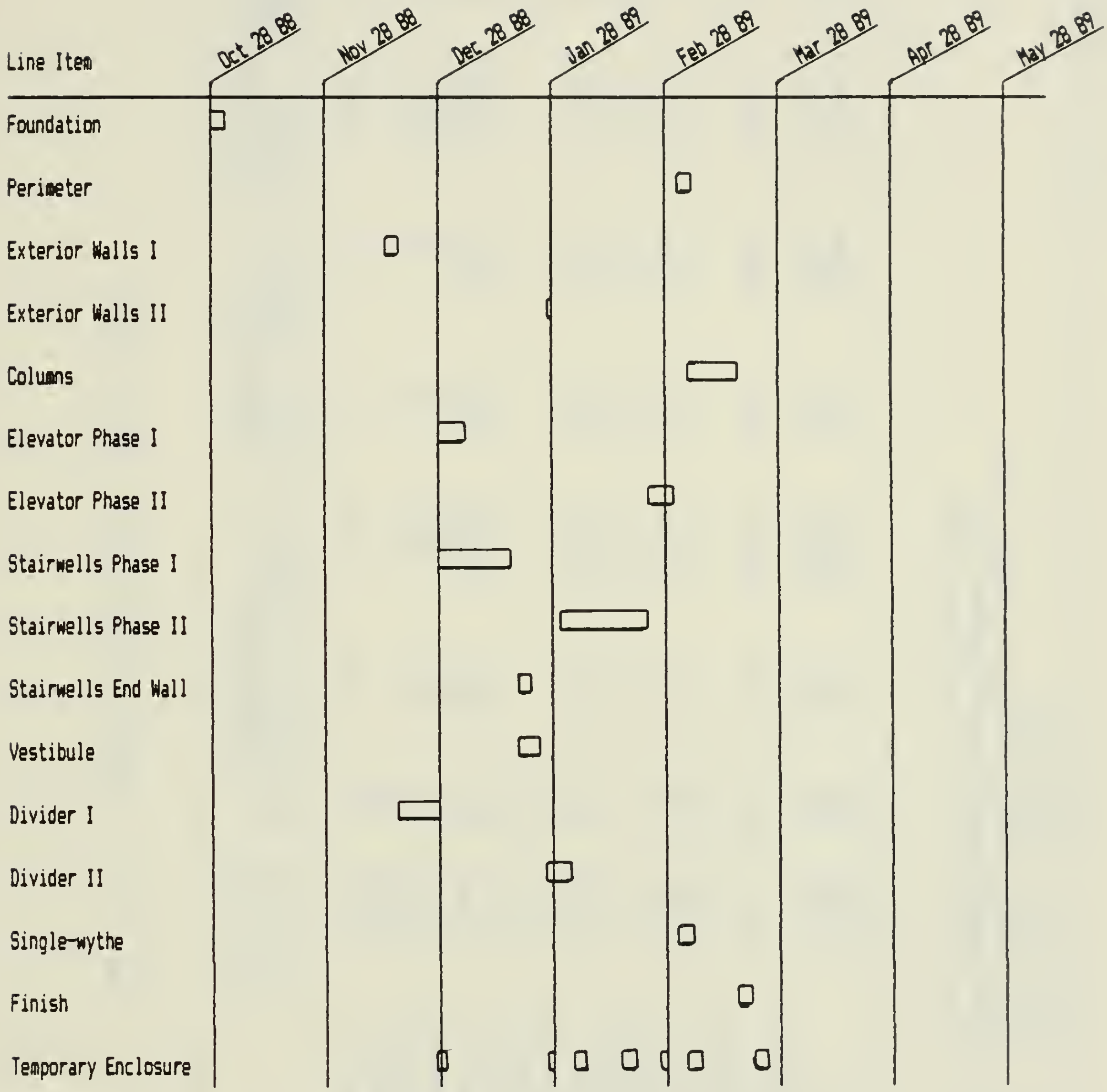

Figure 11. Revised Masonry Schedule for United Federal Bank

Table 12. - Summary of Predicted Productivity

Work-day	Line Item	Line Item Unit Rate (1)	Quantities Item (2)	Quantities Daily (3)	Quantities Cumulative (4)	Work-hours Daily (5)	Work-hours Cumulative (6)	Predicted Unit Rate Daily (7)	Predicted Unit Rate Cumulative (8)
1	CMU Foundation	0.088	35	401	401	32	32	0.080	0.080
	Brick Foundation	0.079	366						
2	Brick Foundation	0.079	405	405	806	32	64	0.079	0.079
3	Brick Foundation	0.079	151	151	957	12	76	0.079	0.079
4	Exterior Walls I	0.141	852	852	1809	120	196	0.141	0.108
5	Exterior Walls I	0.141	321	647	2456	120	316	0.185	0.129
	Divider Walls I	0.193	326						
	Temporary Shelter								
6-8	Divider Walls I	0.193	622	622	4322	120	676	0.193	0.156
9-11	Divider Walls	0.193	373	373	5441	120	1036	0.322	0.190
	Temporary Shelter								
12	Divider Walls	0.193	69	373	5814	120	1156	0.322	0.199
	Stairwells I	0.193	304						
	Temporary Shelter								
13	Stairwells I	0.193	550	550	6364	120	1276	0.218	0.201
	Temporay Shelter								
14-21	Stairwells I	0.193	622	622	11340	120	2236	0.193	0.197
22-27	Stairwells I	0.193	311	710	15600	120	2956	0.169	0.189
	Elevator I	0.150	399						

Column (3) = Sum of column (2) for each Work Day
Column (4) = Sum of daily totals from column (3)
Column (6) = Sum of daily work-hours from column (5)
Column (7) = column (5) - column (3)
Column (8) = column (6) - column (4)

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Table 12. (cont.)

Work-day	Line Item	Line Item Unit Rate (1)	Quantities Item (2)	Quantities Daily (3)	Quantities Cumulative (4)	Work-hours Daily (5)	Work-hours Cumulative (6)	Predicted Unit Rate Daily (7)	Predicted Unit Rate Cumulative (8)
28	Stairwells I	0.193	47	676	16276	120	3076	0.178	0.189
	Elevator I	0.150	241						
	Stairwell End Wal	0.193	372						
	Vestibule	0.193	16						
29-32	Vestibule	0.193	622	622	18764	120	3556	0.193	0.190
33	Vestibule	0.193	1	725	19489	120	3676	0.166	0.189
	Exterior Walls II	0.141	612						
	Divider Walls II	0.193	112						
	Temporary Shelter								
34-36	Divider Walls II	0.193	622	622	21355	120	4036	0.193	0.189
37	Divider Walls II	0.193	415	415	21770	120	4156	0.289	0.191
	Temporary Shelter								
38	Divider Walls II	0.193	180	622	22392	120	4276	0.193	0.191
	Stairwells II	0.193	442						
39	Stairwells II	0.193	591	591	22983	120	4396	0.203	0.191
	Temporary Shelter								
40-42	Stairwells II	0.193	622	622	24849	120	4756	0.193	0.191
43-44	Stairwells II	0.193	311	710	26269	120	4996	0.169	0.190
	Elevator II	0.150	399						

Column (3) = Sum of column (2) for each Work Day
Column (4) = Sum of daily totals from column (3)
Column (6) = Sum of daily work-hours from column (5)
Column (7) = column (5) - column (3)
Column (8) = column (6) - column (4)

(cont. on next page)

Table 12. (cont.)

Work-day	Line Item	Line Item Unit Rate (1)	Quantities Item (2)	Quantities Daily (3)	Quantities Cumulative (4)	Work-hours Daily (5)	Work-hours Cumulative (6)	Predicted Unit Rate Daily (7)	Predicted Unit Rate Cumulative (8)
45	Stairwells II	0.193	334	571	26840	120	5116	0.210	0.191
	Elevator II	0.150	237						
	Temporary Shelter								
46	Stairwells II	0.193	517	517	27357	120	5236	0.232	0.191
	Temporary Shelter								
47-49	Stairwells II	0.193	622	622	29223	120	5596	0.193	0.191
50-51	Stairwells II	0.193	311	710	30643	120	5836	0.169	0.190
	Elevator II	0.150	399						
52	Stairwells II	0.193	437	675	31318	120	5956	0.178	0.190
	Elevator II	0.150	238						
53	Stairwells II	0.193	180	1008	32326	120	6076	0.119	0.188
	Perimeter Walls	0.103	828						
54	Perimeter Walls	0.103	376	1060	33386	120	6196	0.113	0.186
	Single Wythe	0.247	197						
	CMU Columns	0.107	200						
	Brick Columns	0.112	287						
	Temporary Shelter								
55	CMU Columns	0.107	180	438	33824	120	6316	0.274	0.187
	Brick Columns	0.112	258						
	Temporary Shelter								

Column (3) = Sum of column (2) for each Work Day
Column (4) = Sum of daily totals from column (3)
Column (6) = Sum of daily work-hours from column (5)
Column (7) = column (5) - column (3)
Column (8) = column (6) - column (4)

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Table 12. (cont.)

Work-day	Line Item	Line Item Unit Rate (1)	Quantities Item (2)	Quantities Daily (3)	Quantities Cumulative (4)	Work-hours Daily (5)	Work-hours Cumulative (6)	Predicted Unit Rate Daily (7)	Predicted Unit Rate Cumulative (8)
56-61	CMU Columns	0.107	180	438	36452	48	6604	0.110	0.181
	Brick Columns	0.107	258						
62	CMU Columns	0.107	70	433	36885	48	6652	0.111	0.180
	Brick Columns	0.112	363						
63	Brick Columns	0.112	430	430	37315	48	6700	0.112	0.180
64	Brick Columns	0.112	15	203	37518	48	6748	0.236	0.180
	Finish	0.247	188						
65	Finish	0.247	195	195	37713	48	6796	0.246	0.180
66	Finish	0.247	6	6	37720	17	6813	2.833	0.181
	Temporary Shelter								

Column (3) = Sum of column (2) for each Work Day
Column (4) = Sum of daily totals from column (3)
Column (6) = Sum of daily work-hours from column (5)
Column (7) = column (5) - column (3)
Column (8) = column (6) - column (4)

Productivity Trend Curve

Once the schedule has been adjusted to eliminate excessive manpower requirements and the activity duration calculated, the productivity trend curve is be plotted. This curve is the cumulative unit rate versus either work days or cumulative quantity.

The productivity trend curve showing cumulative productivity versus cumulative quantities is shown in Figure 12. The curve shows that the easy work is planned for the first part of the activity, and the more difficult will be done during the production phase.

COMPARISON OF PRODUCTIVITY TREND CURVES

The predicted productivity trend curves for the four different methods are shown in Figure 13. As can be seen, the curves differ considerably, especially during the first third of the work. The Factor Model is the only method that shows a worsening trend reflecting the easy work being done first followed by the more difficult work.

FACTOR MODEL FORECAST

A work-hour forecast based on the Factor Model was calculated using Equation 7 from the data in Tables 12 and 2. A forecast was made at the end of week three (work day 7) for the sample project as follows:

$$\text{Forecast Work-hours} = (0.181 - 0.107 + 0.181) \times 37{,}720$$

$$\text{Forecast Work-hours} = 9{,}619 \text{ work-hours}$$

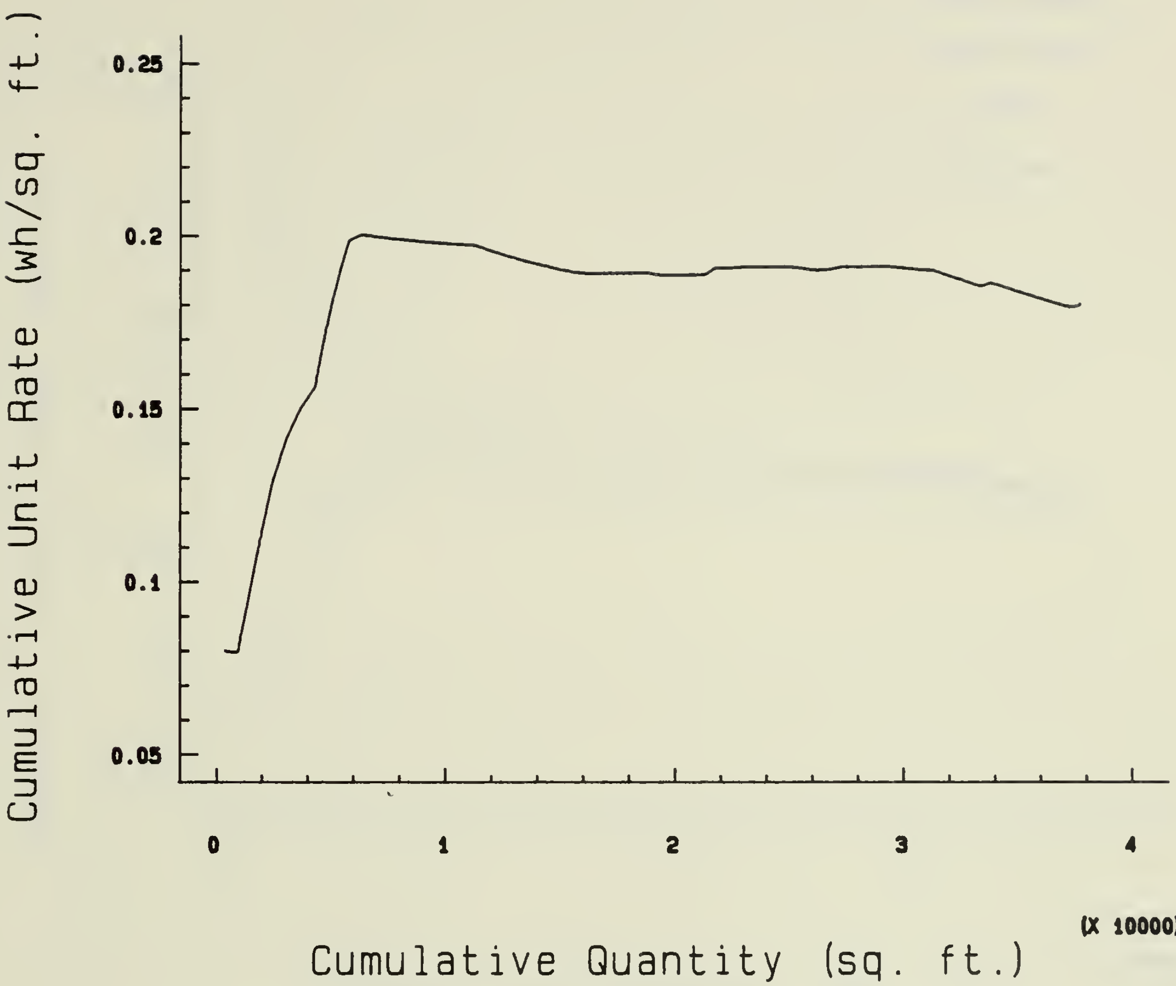

Figure 12. Productivity Trend Curve for the Factor Model

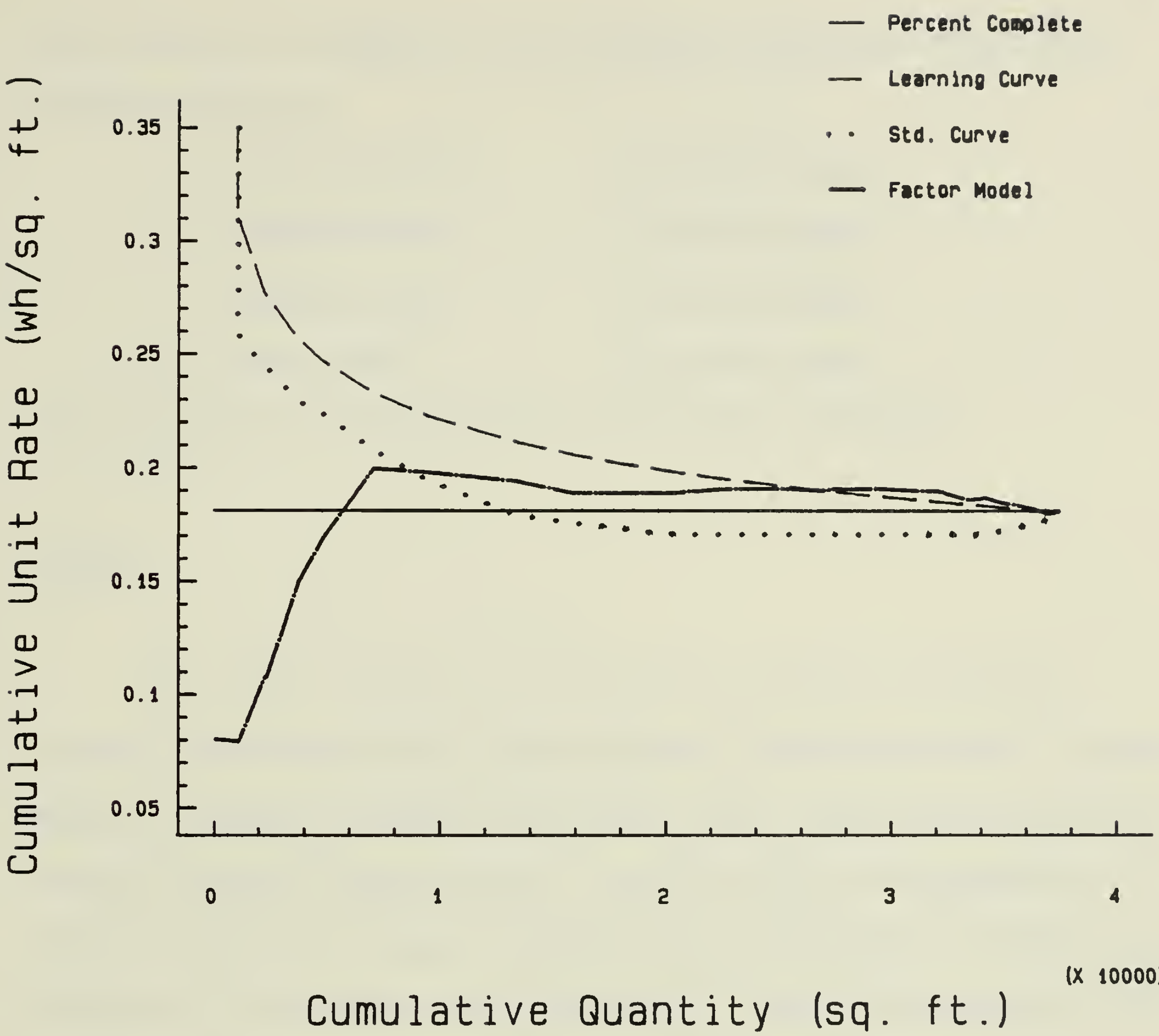

Figure 13. Productivity Trend Curves for the Four Forecasting Methods

This value can be compared to the forecasts developed for the other methods which were:

Percent Complete	6,843 work-hours
Learning Curve	3,168 work-hours
Standard Curve	5,052 work-hours
Factor Model	9,619 work-hours

As can be seen, the forecasts are substantially different.

SUMMARY

This chapter outlined the procedures necessary to develop a forecast for the case study project based on the factor model. The case study is a uniquely designed, multistory steel frame bank building with extensive interior masonry walls. The first step in forecasting with the factor model is to make a detailed line item quantity estimate based on work type, work phase and design detail. Daily unit rates and work days are calculated for each line item. The quantity estimate and a milestone schedule are then used to develop a productivity trend curve which is then used to forecast the work-hours at completion.

The productivity trend curve for the factor model was compared with the productivity trend curves for the other methods. There are significant differences, especially in the first third of the activity, but these differences are reflected in the work-hour forecasts.

CHAPTER 4

ACTUAL PROGRESS OF PROJECT

This chapter describes the progress of the masonry construction on the case study project. The progress was monitored on a daily basis in accordance with the procedures outlined in the Productivity Measurement Manual [5]. Daily productivity was calculated and disruptions to the work were noted.

EXECUTION PARAMETERS AND PRODUCTIVITY

The project design was unique and was unlike the projects used by Sanders in developing the coefficients for the Factor Model (see Table 6). Furthermore, project execution was not efficient and orderly. The work was done in the winter which resulted in changes to the planned schedule. The scheduled work week was five days. There was no overtime worked on the project, and the work week sometimes was shorter than scheduled due to adverse weather or sequencing problems.

The actual quantities installed, 37,440 square feet of standard units, varied from the initial estimate, 37,719 square feet of standard units, by only 1%, a negligible difference. On the other hand, the total work-hours expended, 8,881, exceeded the initial estimate of 6,813 work-hours by more than 30%.

The actual daily productivity is shown in Figure 14 and indicates that in general, the crew was not able to develop any consistency in their work. The figure also shows that 35% of the work days were

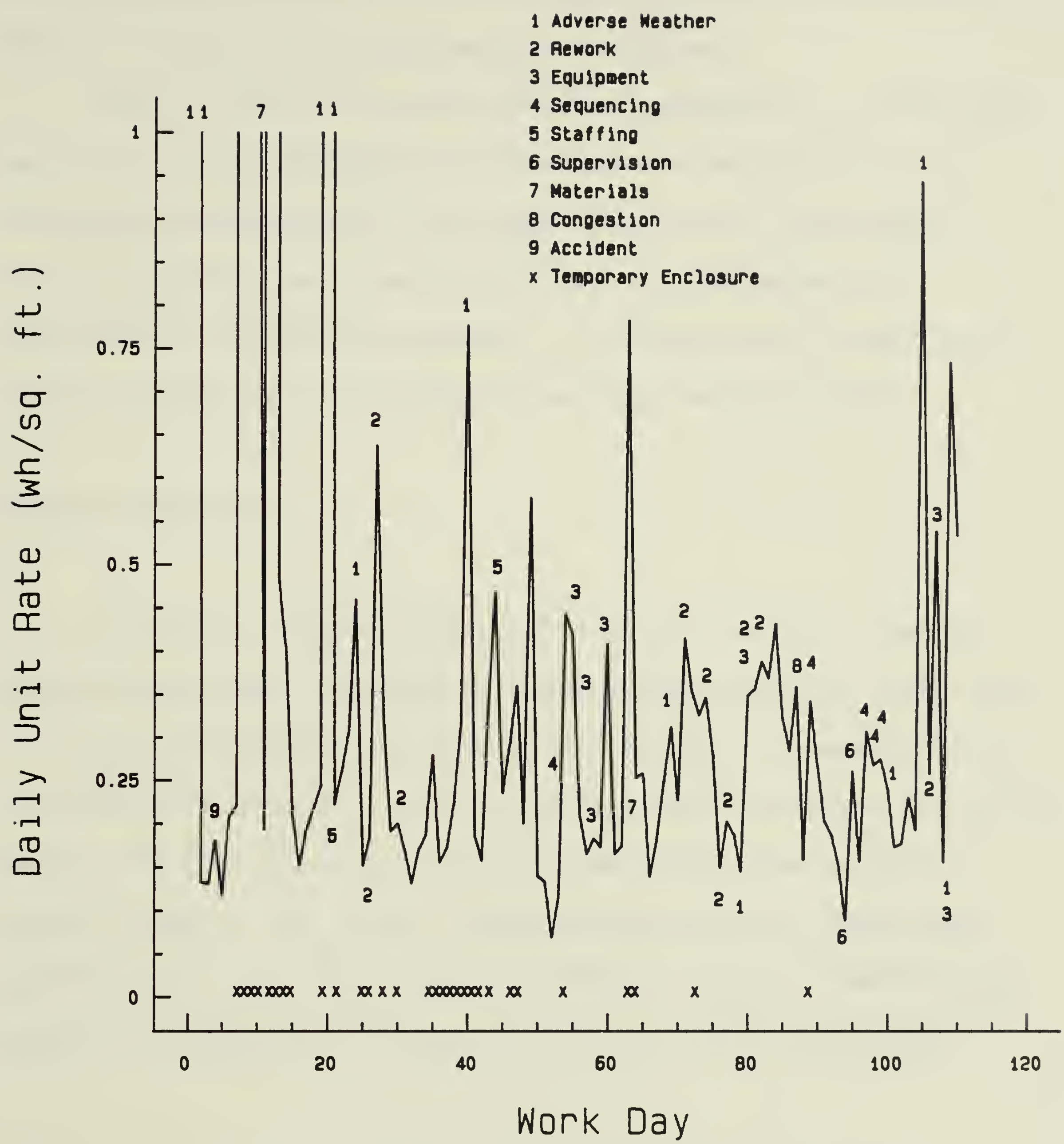

Figure 14. Daily Masonry Productivity on United Federal Bank

disrupted and that 25 of the first 50 work days included considerable effort in building and moving temporary enclosures.

Figure 15 shows the actual cumulative productivity. Productivity was better at the beginning of the work because the relatively easy foundations were being done. The significant rise in productivity shortly thereafter was caused by the onset of cold weather and construction of temporary enclosures. A further loss of productivity occurred because half of the last 40 work days were disrupted.

SCHEDULE VARIATIONS

The as-built schedule (Figure 16) that the contractor used to complete the project differed from the as planned schedule (Figure 10). This change in sequencing resulted largely because of construction of the temporary enclosures. When an enclosure was constructed, all of the masonry inside of the enclosed area was completed before moving to another location. The initial scheduling logic did not reflect this pattern of work. As a result of the schedule revisions, some finished masonry was damaged which necessitated rework later in the project.

FACTORS AFFECTING CONTRACTOR PERFORMANCE

Throughout the activity, the contractor experienced problems that hindered execution. These are described below.

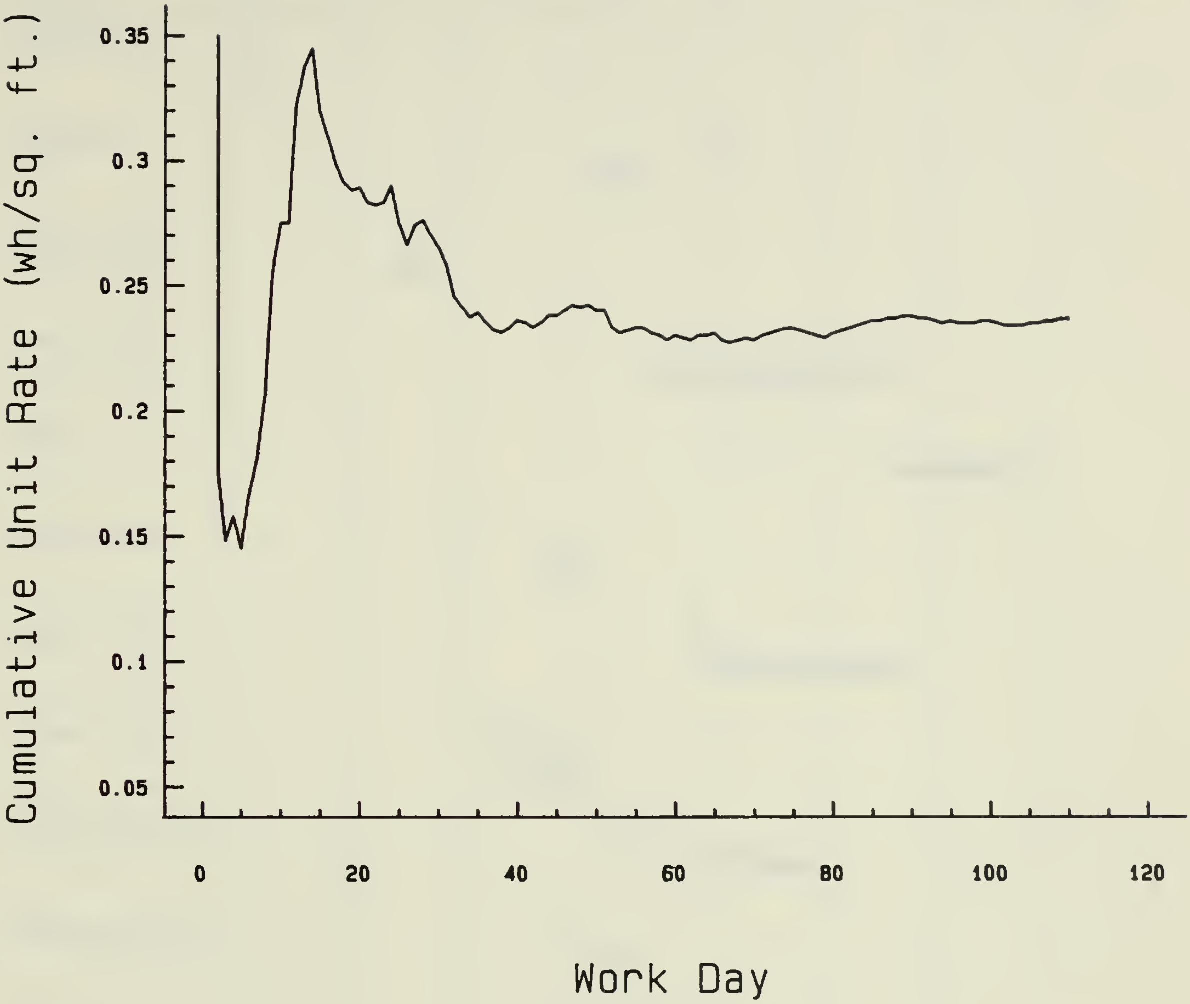

Figure 15. Cumulative Masonry Productivity on United Federal Bank

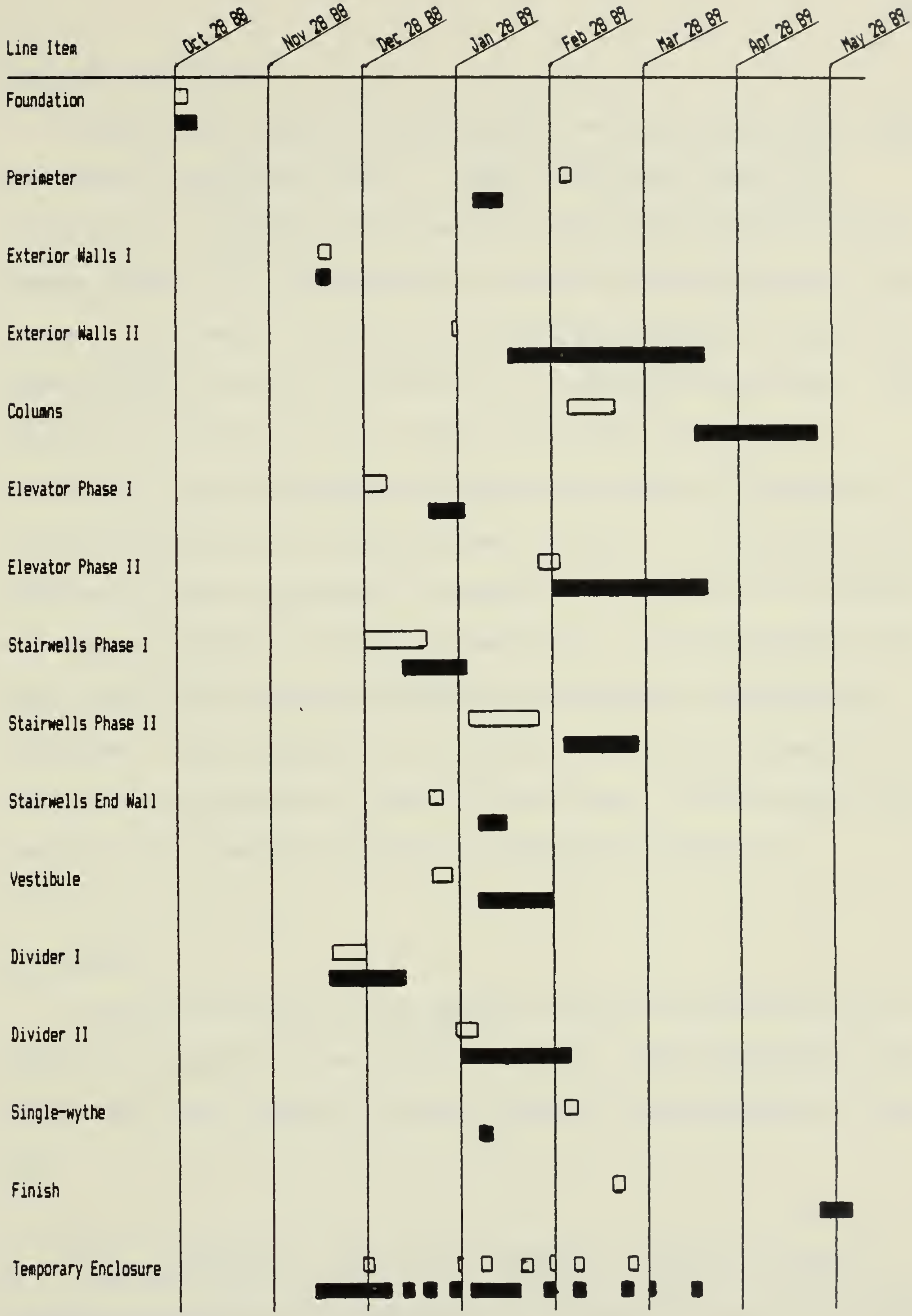

Figure 16. As Built Masonry Schedule for United Federal Bank

Temporary Enclosures

Masonry work started in late October, and the superintendent began cold weather protection on day 7. These activities included the construction of temporary enclosures and heating the area with portable propane heaters. The construction of the first enclosures was not well planned. As a result, the shelters constructed on days 7, 8 and 9 were redone because they were not effective in enclosing the work area. This resulted in time being lost to rebuild the initial enclosures. Thereafter, the work progressed unimpeded except when the location of the work changed and the enclosures were relocated. The enclosures also required continual maintenance to preserve the integrity of the plastic sheeting and maintain the required temperature. An estimated 600 work-hours over 30 work days were attributed to working on the temporary enclosures. This exceeded the 412 work-hours that were estimated for the temporary enclosures by almost 200 work-hours. The days when work was done on the temporary shelter are indicated on Figure 14.

Disruptions

The actual duration of the masonry work was 110 work days, 39 of these days experienced some type of disruption. These disruptions were grouped into nine categories listed in Table 13 and identified on Figure 14.

Adverse Weather.-- Despite the temporary enclosures, adverse weather affected 10% of the work days. On 11 days the work of the crew was disrupted by weather. These are days 1, 2, 19, 20, 24, 40, 68, 79,

Table 13. - Disruptions

Type	No. of Occurrences
Adverse Weather	11
Rework	10
Equipment	7
Sequencing	5
Staffing	2
Supervision	2
Material	2
Congestion	1
Accidents	1

100, 105 and 108. The conditions were such that the crew quit early or continued working but at a slower pace. Principal weather events were rain on 7 days and cold temperatures on 2 days. The remaining two days were attributed to snow and high winds.

The temporary shelters did not eliminate the disruptions on days 19, 20 and 24, because the workers were concerned about travel conditions and either showed up late or went home early due to heavy snow and freezing rain. On days 40 and 68 heavy rains caused the enclosure to leak excessively and the craftsmen went home early.

Rework.-- Rework occurred ten times. This was a result of design changes on day 106, poor workmanship on days 73, 77 and 82, misreading drawings on days 27, 28, and 80, and repairing damaged work on days 30, 71, and 76.

Equipment.-- On days 55, 56, 58, 60, 80, 107 and 108 the forklift was either down for maintenance or off site. The home office did not provide any other mechanized means of material handling.

Sequencing.-- On five days, disruptions were recorded because the masonry crew had to wait or was moved to another area because work scheduled for other trades was not completed. Before the tops of the columns could be finished the masons has to wait for the carpenters to build plywood soffits and for roofers to install flashing material. This occurred on days 89, 97, 98, and 99. The crew was delayed on day 53 because the temporary shelter had to be relocated.

Staffing.-- On days 22 and 43 more workers showed up in the morning than the foreman had planned for, and not enough work was laid out to keep them busy.

Supervision.-- On days 94 and 95 the foreman and part of the crew went fishing.

Material.-- Material shortages affected the project on two separate occasions. The crew was waiting for bricks to be delivered on day 10 and mortar on day 64.

Congestion.-- The work was congested on day 87 when the carpenters installed drywall in the same location as the masons were fitting the stairwell walls to the roof.

Accidents.-- A lost time accident occurred on day 5 when a laborer fell off the scaffolding. The masonry production was disrupted, and the crafts were sent home 2 hours early.

Impact of Disruptions

Sanders [4:159] developed disruption indices for the primary types of disruptions experienced during the execution of a project. These indices are summarized in Table 14 and show the relative output on days when disruptions are present.

To assess the impact of disruptions, the total recorded work-hours

Table 14. - Disruption Indices

Type of Disruption	Index
None	1.00
Weather Events	0.32
Congestion	0.35
Sequencing	0.25
Materials	0.54
Rework	0.41
Supervision	0.59
Staffing	0.58
Equipment *	0.45

* value was calculated from case study data

Source: Sanders, 1989

for each disrupted day was multiplied by the corresponding index. This product is the number of work-hours that should have been expended to produce the same output. Removing the effects of disruptions decreased the cumulative work-hours by 1,569 work-hours. This is 23% of the total work-hour overrun. The total adjusted work-hours still exceeded the estimate by 499 work-hours or 7%. The cumulative unit rate was reduced from 0.237 to 0.195 wh/ft^2. Figure 17 shows the actual and adjusted cumulative productivity.

CONSTRUCTABILITY

The contractor's productivity was impacted by the unique design of the building. The building had a very steep sloping roof and required extensive cutting of the abutting masonry to match the slope. About 83% of the masonry work was double or triple-wythe brick walls and 55% were interior walls. The length of walls were not sized to be an integer multiple of the size of the masonry unit used. This meant that masonry units had to be cut for each course of masonry. Another feature that affected constructability was that 17 out of 30 corners of the first floor perimeter wall were nonrectangular.

OTHER CONSIDERATIONS

A common occurrence during the duration of the activity was an unplanned fluctuation in the crew size. This is shown in Figure 18. Some of this variation can be attributed to different phases of the work

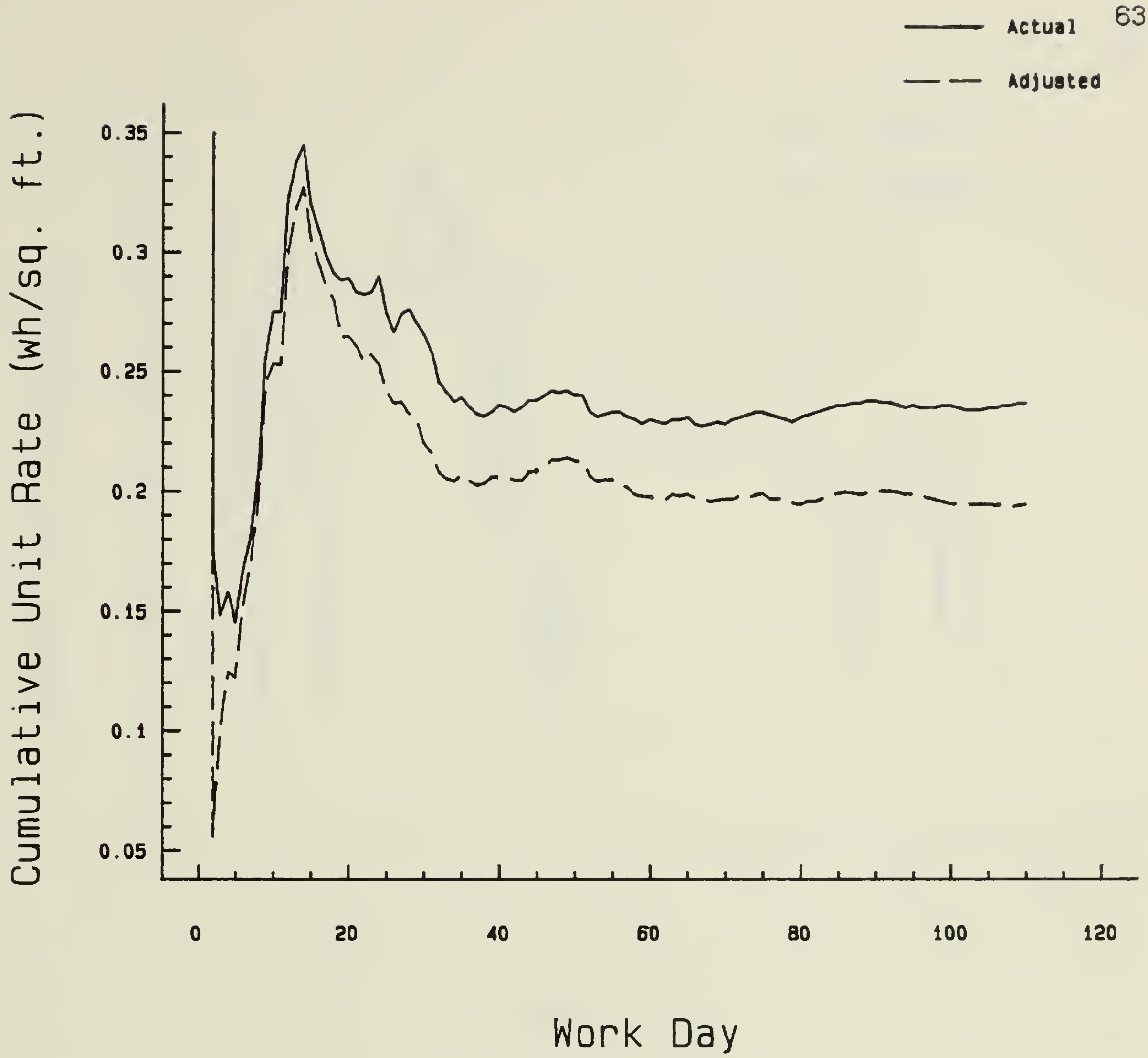

Figure 17. Actual and Adjusted Productivity

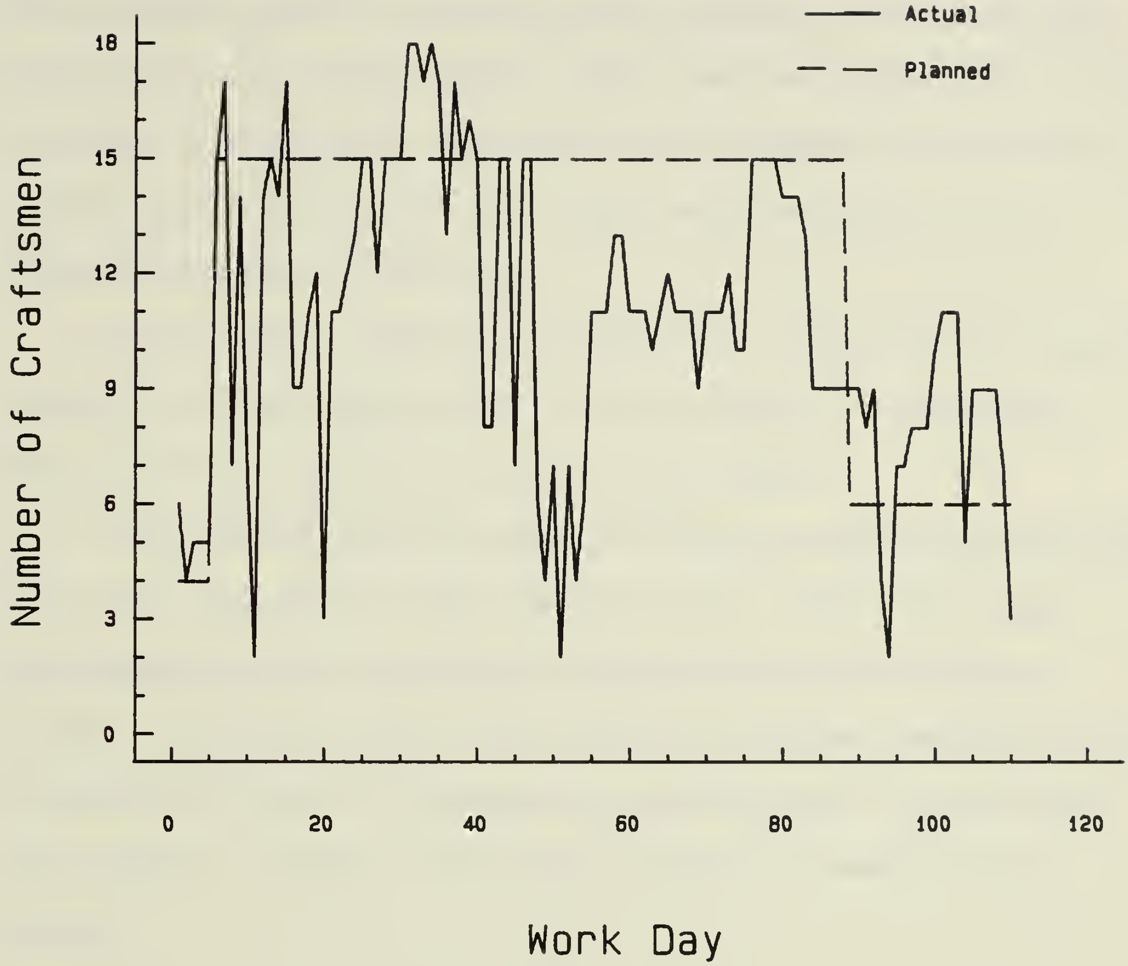

Figure 18. Planned and Actual Crew Size

and minor absenteeism. But, most of the variation was due to the home office sending workers to and from other projects in the area without informing the site superintendent. Many times the foreman did not know the number of craftsmen he would have until the start of the work day. To compensate, the foreman tried to keep extra work laid out for unexpected increases in crew size.

On day 55 the a totally new masonry crew, except for the foreman, was hired, the old crew was sent to other projects. A new masonry foreman started on day 104 to complete the project.

Another aspect of this project was that the masonry crew was part of the prime contractor's open shop work force. This led to some disagreements between the project superintendent and the masonry foreman. The superintendent did not have any laborers assigned to him for general site work, so, whenever he needed support, he would use mason tenders. Generally, this did not appear to impede the job progress.

SUMMARY

The actual progress of the project was impacted by many conditions and events. The actual productivity exceeded the estimated productivity by over 30%. The work was done in the winter and the contractor was required to construct, move and dismantle temporary enclosures for 75% of the masonry activity. The contractor's planned schedule was revised after the construction of the temporary enclosures and resulted in some of the finished masonry work being damaged, thus necessitating rework.

Disruptions occurred on 39 of 110 work days. Their impact was discounted with the use of indices and accounted for 18% of the work-hour overrun. Principal disruptions were 11 days for weather and 10 days for rework.

Another factor that influenced the project was the unique design of the building which required extra care in lay out and construction.

CHAPTER 5

COMPARISON OF FORECASTING TECHNIQUES

This chapter compares the accuracy of the four forecasting techniques described in Chapters 2 and 3. Forecasts were made at weekly intervals based on the cumulative unit rate and cumulative equivalent quantity of the standard masonry unit.

ADEQUACY OF CASE STUDY

The United Federal Bank provided an adequate test for comparing the forecasting techniques because of the variety of factors that affected the work.

Five major factors were present that are difficult to include in a forecasting model. These are the unusual design, schedule variances to accommodate the weather, less than ideal management practices, adverse weather conditions, and disruptions. Each one of these items increased the level of uncertainty with respect to the accuracy of the forecast.

WEEKLY FORECASTS

The masonry activity duration was 27 weeks, for which 26 weekly forecasts were made. Figure 19 shows the productivity trend curves for each forecasting method and the actual productivity. In general, the trend curve based on the Factor Model most closely approximates the actual productivity trends.

The weekly forecasts are summarized in Table 15 and plotted on

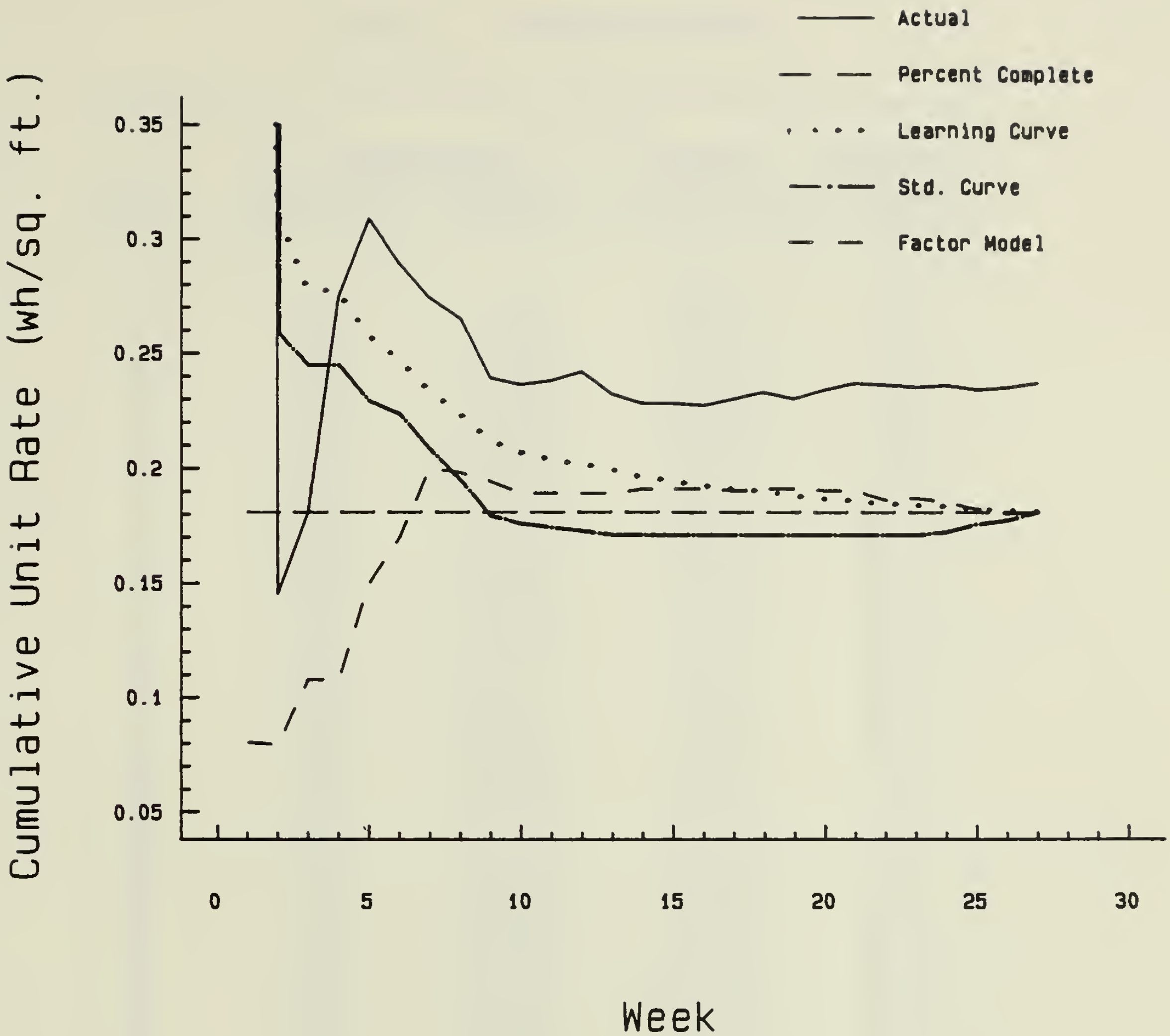

Figure 19. Actual Productivity and Trend Curves

Table 15. - Weekly Forecasts

Week	Cumulative Work-hours (1)	Cumulative Quantity (2)	Actual Productivity (3)	Percent Complete (4)
1	9	2	5.202	0.0
2	155	1070	0.145	2.8
3	407	2243	0.181	5.9
4	635	2312	0.275	6.1
5	1151	3729	0.309	9.9
6	1404	4852	0.289	12.9
7	1938	7070	0.274	18.7
8	2514	9476	0.265	25.1
9	3208	13426	0.239	35.6
10	3748	15902	0.236	42.2
11	4171	17498	0.238	46.4
12	4491	18536	0.242	49.1
13	4678	20177	0.232	53.5
14	5126	22437	0.228	59.5
15	5390	23692	0.228	62.8
16	5830	25629	0.227	67.9
17	6156	26780	0.230	71.0
18	6412	27532	0.233	73.0
19	6811	29584	0.230	78.4
20	7276	31042	0.234	82.3
21	7588	32040	0.237	84.9
22	7898	33424	0.236	88.6
23	8026	34177	0.235	90.6
24	8216	34850	0.236	92.4
25	8521	36368	0.234	96.4
26	8687	36910	0.235	97.9
27	8881	37440	0.237	99.3

Column (3) = column (1) - column (2)
Column (4) = column (2) - 37,720

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Table 15. (cont.)

Week	Percent Complete Forecast Unit Rate (5)	Percent Complete Forecast Error (6)	Learning Curve Forecast Unit Rate (7)	Learning Curve Forecast Error (8)
1	5.202	4.965	4.557	4.320
2	0.145	-0.092	0.015	-0.222
3	0.181	-0.056	0.084	-0.153
4	0.275	0.038	0.179	-0.058
5	0.309	0.072	0.233	-0.004
6	0.289	0.052	0.223	-0.014
7	0.274	0.037	0.222	-0.015
8	0.265	0.028	0.223	-0.014
9	0.239	0.002	0.208	-0.029
10	0.236	-0.001	0.211	-0.026
11	0.238	0.001	0.216	-0.021
12	0.242	0.005	0.221	-0.016
13	0.232	-0.005	0.214	-0.023
14	0.228	-0.009	0.213	-0.024
15	0.228	-0.009	0.215	-0.022
16	0.227	-0.010	0.216	-0.021
17	0.230	-0.007	0.220	-0.017
18	0.233	-0.004	0.224	-0.013
19	0.230	-0.007	0.223	-0.014
20	0.234	-0.003	0.229	-0.008
21	0.237	0.000	0.232	-0.005
22	0.236	-0.001	0.233	-0.004
23	0.235	-0.002	0.232	-0.005
24	0.236	-0.001	0.234	-0.003
25	0.234	-0.003	0.233	-0.004
26	0.235	-0.002	0.234	-0.003
27	0.237	0.000	0.237	0.000

Column 6 = column 5 - 0.237
Column 8 = column 7 - 0.237

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Table 15. (cont.)

Week	Performance Factor (9)	Standard Curve Forecast Unit Rate (10)	Standard Curve Forecast Error (11)	Factor Model Forecast Unit Rate (12)	Factor Model Forecast Error (13)
1	0.01	0.052	-0.185	5.303	5.066
2	0.70	0.102	-0.136	0.247	0.010
3	0.74	0.134	-0.103	0.254	0.017
4	0.74	0.204	-0.033	0.348	0.111
5	0.79	0.244	0.007	0.340	0.103
6	0.81	0.234	-0.003	0.300	0.063
7	0.87	0.238	0.001	0.255	0.018
8	0.93	0.246	0.009	0.248	0.011
9	1.01	0.241	0.004	0.226	-0.011
10	1.03	0.243	0.006	0.228	-0.009
11	1.04	0.248	0.011	0.230	-0.007
12	1.05	0.254	0.017	0.234	-0.003
13	1.06	0.246	0.009	0.224	-0.013
14	1.06	0.242	0.005	0.218	-0.019
15	1.06	0.242	0.005	0.218	-0.019
16	1.06	0.241	0.004	0.217	-0.020
17	1.06	0.244	0.007	0.221	-0.016
18	1.06	0.247	0.010	0.223	-0.014
19	1.06	0.244	0.007	0.220	-0.017
20	1.06	0.248	0.011	0.225	-0.012
21	1.06	0.251	0.014	0.228	-0.009
22	1.06	0.250	0.013	0.231	-0.006
23	1.06	0.249	0.012	0.229	-0.008
24	1.05	0.248	0.011	0.232	-0.005
25	1.03	0.241	0.004	0.233	-0.004
26	1.02	0.240	0.003	0.236	-0.001
27	1.00	0.237	0.000	0.237	0.000

Column (11) = column (10) - 0.237
Column (13) = column (12) - 0.237

Figure 20. Figure 21 shows the relative error, which is the forecasted unit rate minus 0.237 which is the actual unit rate at completion. A variance of 0.02 wh/ft^2 or approximately 10% is applied as being an acceptable forecast. This variance is shown on Figures 20 and 21 as the upper and lower limits. These data are also summarized in Table 15. Notice that the percent complete forecast and the actual cumulative productivity are the same curve.

The forecasts for each method varied widely at the beginning and then converged as the activity neared completion. During weeks 4 and 5, construction of the temporary enclosures took place. This work severely impacted productivity. The impact is shown in the cumulative productivity for the following three to four weeks. Beginning with week 20, disruptions were recorded on 14 of the remaining 27 work days causing an unexpected loss of productivity. These disruptions caused the final unit rate to be higher. The forecast for the first week is especially variable but covers only nine work-hours.

Forecast Results

The next section discusses specifics about each method.

Percent Complete.-- The forecasts for the percent complete method oscillate considerably throughout. It did not produce a forecast within 10% of the final productivity until week 9.

Learning Curve.-- The learning curve produced a forecast within 10% of the final productivity from week 5 to week 8, on week 12, and

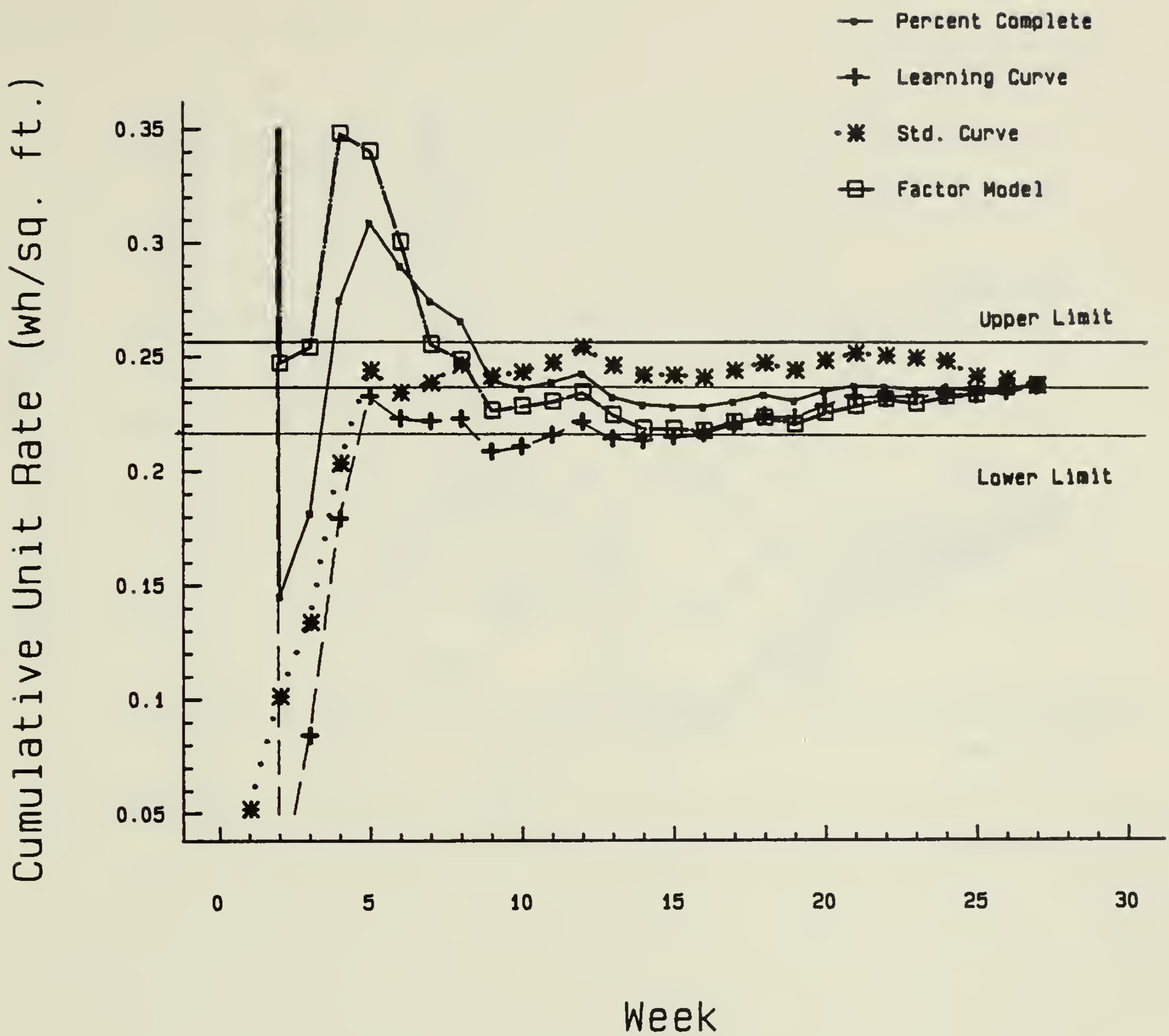

Figure 20. Weekly Productivity Forecasts

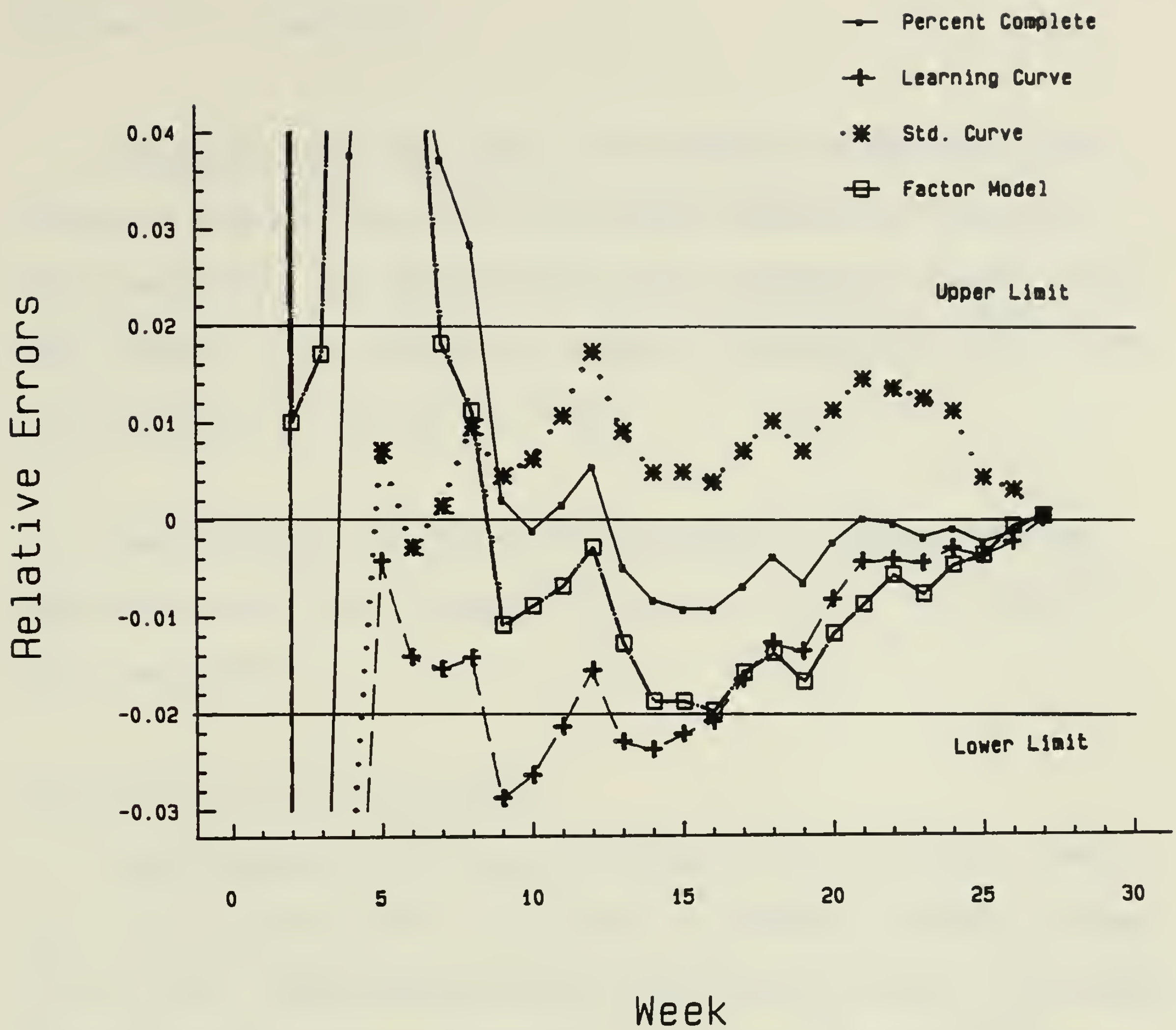

Figure 21. Relative Forecasting Errors

from week 17 to completion.

Standard Productivity Curve.-- The standard productivity curve produced a forecast within 10% of the final productivity from week 5 until completion. But the forecasts do not converge as rapidly as the other methods. This reflects the intuitive assumptions that were used in the selection of the standard curve.

Factor Model.-- The Factor Model produced a forecast that was within 10% of the final productivity from week 2 to 3, then from week 7 until completion.

Evaluation of Forecast Techniques

Four approaches were used to evaluate the four methods. These are: 1) the earliest point in time that the forecast is within a range of 0.02 wh/ft^2 (approximately 10%) of the final unit rate, 2) the number of weeks that the forecast are within this range, 3) the sum of the absolute error for all 26 weeks, and 4) the sum of the absolute error excluding the first week. The results of the four criteria show mixed results and are summarized in Table 16.

In general, the forecasts for all four methods shows considerable variability during the first third of the work. Thereafter, the forecasts converge to the actual productivity at completion. The initial weekly forecasts should be disregarded as it is based on the expenditure of only 9 work-hours. The standard productivity curve and learning curve performed slightly better than the Factor Model. The

Table 16. - Forecast Accuracies

Forecast Method	Earliest Accurate Week (1)	No. Weeks Within 10% of Final Rate (2)	Absolute Difference (3)	Absolute Difference Less Week 1 (4)
Percent Complete	9	19	5.403	1.083
Learning Curve	5	16	5.058	0.093
Standard Productivity Curve	5	23	0.623	0.438
Factor Model	2	23	5.586	0.520

percent complete approach was least accurate.

Figure 19 shows that the standard productivity curve and the learning curve predict improving productivity in the early stages of the work. The Factor Model predicts the opposite trend. The actual productivity worsened from the outset, and on that basis, the Factor Model produced acceptable forecasts after weeks 2 and 3. During week 4 considerable time was spent by the crew to construct temporary enclosures. This resulted in significant degradation of productivity. When some semblance of normality returned the following week, productivity began to improve as predicted by the standard productivity and learning curves. Thus, the trend during weeks 2 and 3 is consistent with the Factor Model whereas the trend for the period following week 4 is consistent with the learning curve and standard productivity curve.

The standard productivity curve and learning curve methods correctly predicted improving productivity because the output was so bad in week 4 that even the more difficult interior work done thereafter lowered the cumulative average productivity. If the inefficiencies associated with the temporary enclosures had not occurred, it is conceivable that the Factor Model would have given acceptable forecasts for all but the first week. The Factor Model was within 4% of the actual productivity at completion after only 3% of the work had been completed. Thus it appears that the Factor Model is a viable alternative to conventional forecasting techniques.

ADJUSTED WEEKLY FORECASTS

The Factor Model, as currently developed, does not model disruptions because they are not predictable events. Disruption indices listed in Table 13, were used to calculate the adjusted cumulative productivity as described in Chapter 4 and shown in Figure 17. Figure 22 shows the adjusted cumulative productivity and the productivity trend curves of the four forecasting methods. Work-hour forecasts were made with the adjusted curves in the same manner as described in the previous section. The adjusted weekly forecasts are compiled in Table 17 and shown in Figure 23. The relative accuracy is shown in Figure 24.

Effect of Disruptions on Forecasting Accuracy

The adjusted weekly forecasts were evaluated using the same criteria described earlier, and the results are shown in Table 18. The

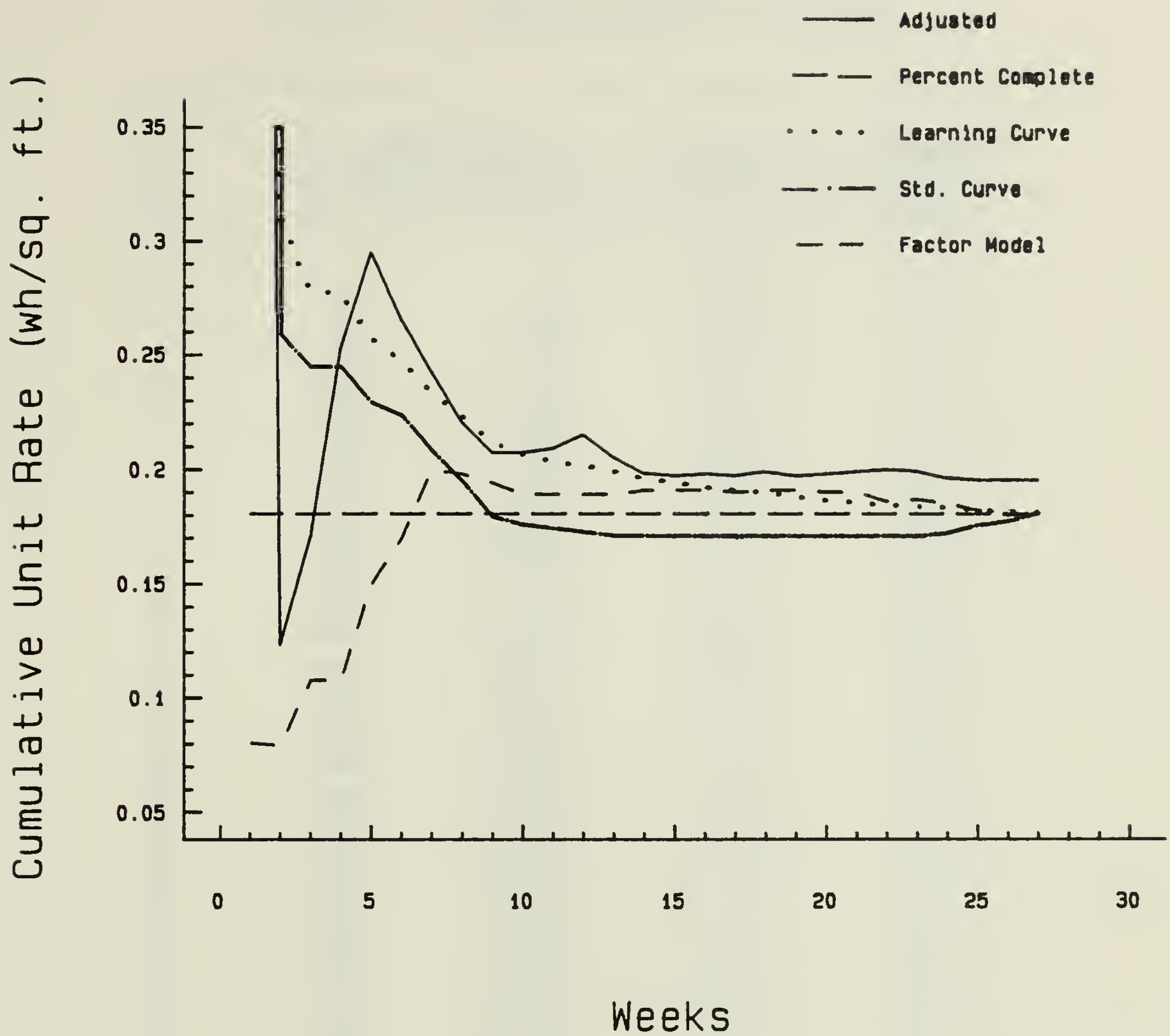

Figure 22. Adjusted Productivity and Trend Curves

Table 17. - Adjusted Weekly Forecasts

Week	Cumulative Work-hours (1)	Cumulative Quantity (2)	Actual Productivity (3)	Percent Complete (4)
1	3	2	1.665	0.0
2	131	1070	0.123	2.8
3	383	2243	0.171	5.9
4	585	2312	0.253	6.1
5	1101	3729	0.295	9.9
6	1286	4852	0.265	12.9
7	1709	7070	0.242	18.7
8	2087	9476	0.220	25.1
9	2781	13426	0.207	35.6
10	3286	15902	0.207	42.2
11	3658	17498	0.209	46.4
12	3978	18536	0.215	49.1
13	4141	20177	0.205	53.5
14	4449	22437	0.198	59.5
15	4664	23692	0.197	62.8
16	5064	25629	0.198	67.9
17	5281	26780	0.197	71.0
18	5481	27532	0.199	73.0
19	5831	29584	0.197	78.4
20	6135	31042	0.198	82.3
21	6282	32040	0.199	84.9
22	6692	33424	0.200	88.6
23	6791	34177	0.199	90.6
24	6838	34850	0.196	92.4
25	7099	36368	0.195	96.4
26	7186	36910	0.195	97.9
27	7312	37440	0.195	99.3

Column (3) = column (2) - column (1)
Column (4) = column (2) - 37,720

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Table 17. (cont.)

Week	Percent Complete Forecast Unit Rate (5)	Percent Complete Forecast Error (6)	Learning Curve Forecast Unit Rate (7)	Learning Curve Forecast Error (8)
1	1.665	1.470	1.020	0.825
2	0.123	-0.072	-0.007	-0.202
3	0.171	-0.024	0.074	-0.121
4	0.253	0.058	0.157	-0.038
5	0.295	0.100	0.219	0.024
6	0.265	0.070	0.199	0.004
7	0.242	0.047	0.190	-0.005
8	0.220	0.025	0.178	-0.017
9	0.207	0.012	0.176	-0.019
10	0.207	0.012	0.182	-0.013
11	0.209	0.014	0.187	-0.008
12	0.215	0.020	0.194	-0.001
13	0.205	0.010	0.187	-0.008
14	0.198	0.003	0.183	-0.012
15	0.197	0.002	0.184	-0.011
16	0.198	0.003	0.187	-0.008
17	0.197	0.002	0.187	-0.008
18	0.199	0.004	0.190	-0.005
19	0.197	0.002	0.190	-0.005
20	0.198	0.003	0.193	-0.002
21	0.196	0.001	0.194	-0.001
22	0.200	0.005	0.197	0.002
23	0.199	0.004	0.196	0.001
24	0.196	0.001	0.194	-0.001
25	0.195	0.000	0.194	-0.001
26	0.195	0.000	0.194	-0.001
27	0.195	0.000	0.195	0.000

Column (6) = column (5) - 0.195
Column (8) = column (7) - 0.195

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Table 17. (cont.)

Week	Performance Factor (9)	Standard Curve Forecast Unit Rate (10)	Standard Curve Forecast Error (11)	Factor Model Forecast Unit Rate (12)	Factor Model Forecast Error (13)
1	0.01	0.017	-0.178	1.766	1.571
2	0.70	0.086	-0.109	0.225	0.030
3	0.74	0.127	-0.068	0.244	0.049
4	0.74	0.187	-0.008	0.326	0.131
5	0.79	0.233	0.038	0.326	0.131
6	0.81	0.215	0.020	0.276	0.081
7	0.87	0.211	0.016	0.223	0.028
8	0.93	0.205	0.010	0.203	0.008
9	1.01	0.209	0.014	0.194	-0.001
10	1.03	0.213	0.018	0.199	0.004
11	1.04	0.217	0.022	0.201	0.006
12	1.05	0.226	0.031	0.207	0.012
13	1.06	0.217	0.022	0.197	0.002
14	1.06	0.210	0.015	0.188	-0.007
15	1.06	0.209	0.014	0.187	-0.008
16	1.06	0.210	0.015	0.188	-0.007
17	1.06	0.209	0.014	0.188	-0.007
18	1.06	0.211	0.016	0.189	-0.006
19	1.06	0.209	0.014	0.187	-0.008
20	1.06	0.210	0.015	0.189	-0.006
21	1.06	0.211	0.016	0.190	-0.005
22	1.06	0.212	0.017	0.195	0.000
23	1.06	0.211	0.016	0.193	-0.002
24	1.05	0.206	0.011	0.192	-0.003
25	1.03	0.201	0.006	0.194	-0.001
26	1.02	0.199	0.004	0.196	0.001
27	1.00	0.195	0.000	0.195	0.000

Column (11) = column (10) - 0.195
Column (13) = column (12) - 0.195

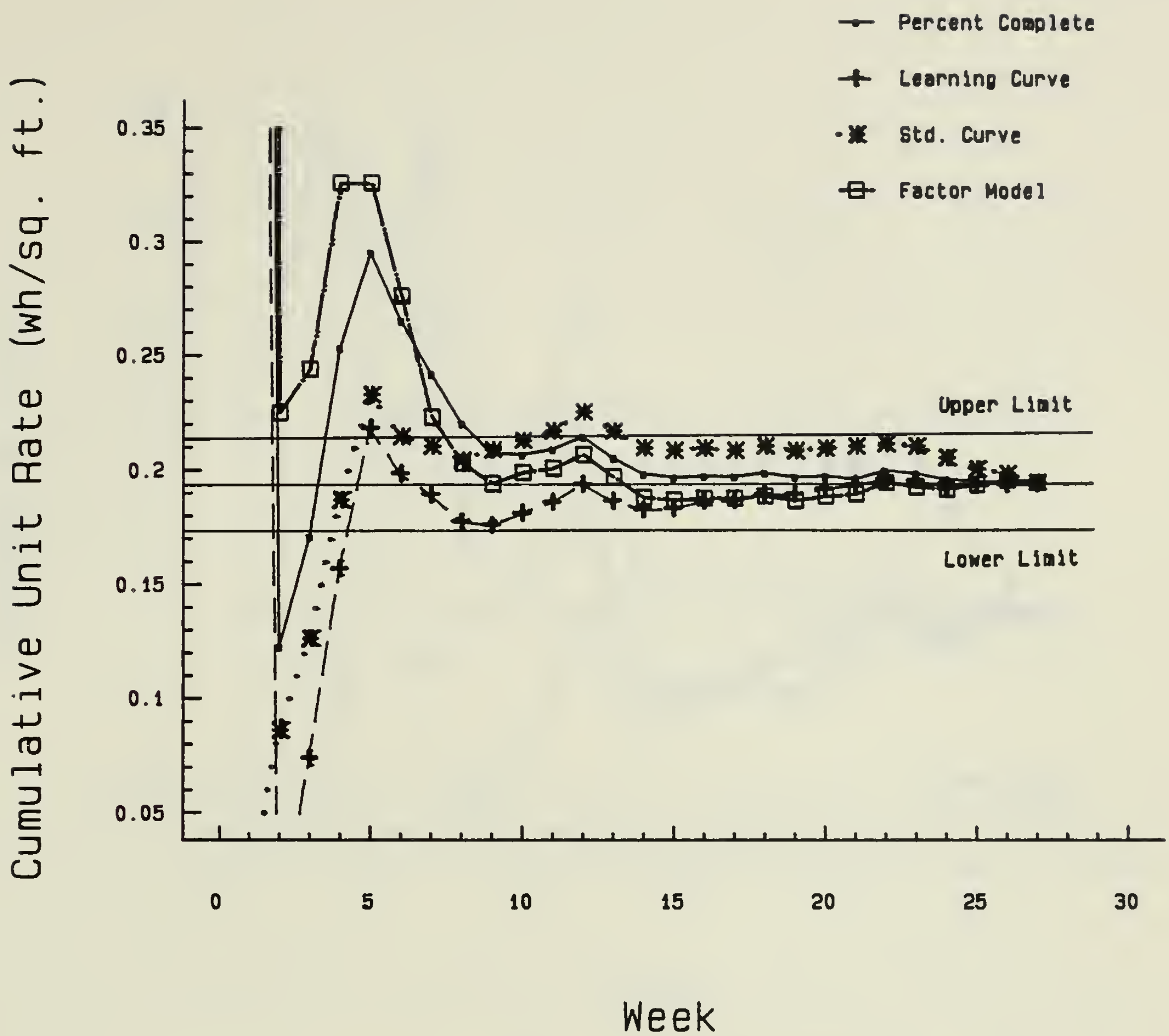


Figure 23. Adjusted Weekly Productivity Forecasts

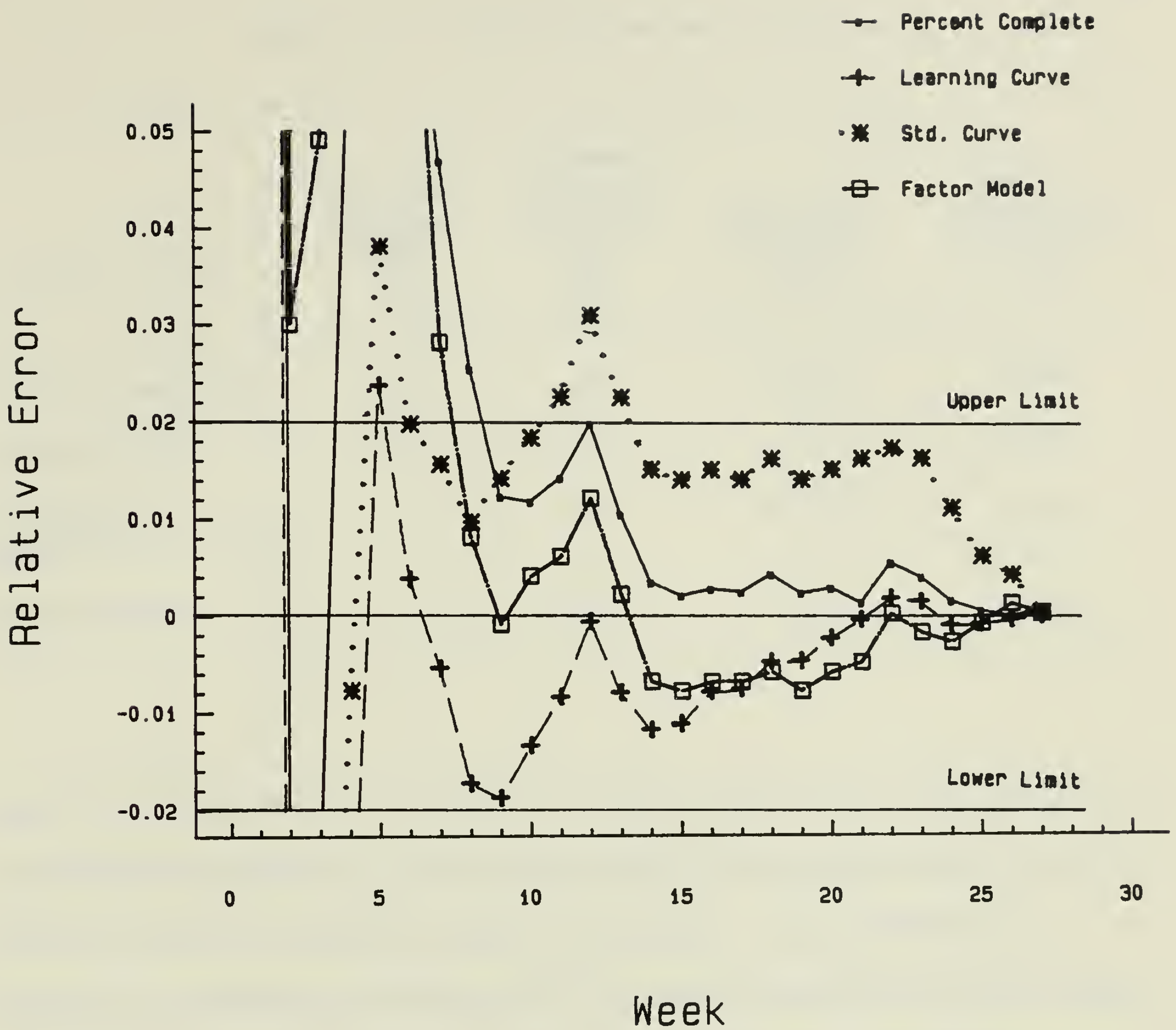


Figure 24. Adjusted Relative Forecasting Errors

Table 18. - Adjusted Forecast Accuracies

Forecast Method	Earliest Accurate Week (1)	Weeks Within 10% of Final Rate (2)	Absolute Difference (3)	Absolute Difference Less Week 1 (4)
Percent Complete	9	19	1.965	0.496
Learning Curve	6	22	1.342	0.518
Standard Productivity Curve	4	20	0.725	0.547
Factor Model	9	19	2.115	0.544

absolute differences for all of the methods improved but the ability of the different methods to accurately predict productivity early in the activity and for successive weeks was reduced. This decrease in accuracy is because the majority of the disruptions did not occur until the last half of the activity. The largest single, adverse impact to productivity was caused by the work on the temporary shelters in the first part of the activity, but adjustments were not made for this event. The adjustments only improved the forecasts in the last half of the activity.

SUMMARY

The project selected for the case study was an adequate test of the different forecasting methods due to the unique design, large number

of disruptions, less than ideal management practices, and wide variance in the weather conditions causing changes in the schedule. Each one of these items increased the uncertainty of the forecasting accuracy.

Weekly forecasts were made for 26 of the activity´s 27 week duration. All of the methods produced divergent forecasts throughout the first third of the activity. This was because considerable work-hours were expended constructing temporary enclosures. When the work on the temporary enclosures was finished and masonry work resumed, productivity improved as predicted by the learning curve and standard productivity curve even though more difficult masonry work was being done.

The Factor Model produced a forecast within 4% of the final productivity after only 3% of the work had been completed. If the inefficiencies associated with the temporary enclosures had not occurred it is conceivable that the Factor Model could have given acceptable forecasts for all but the first week. Thus, it appears that the Factor Model is a viable alternative to conventional forecasting techniques.

CHAPTER 6

CONCLUSIONS

This report compares four work-hour forecasting methods. These are percent complete, learning curve, standard productivity curve and Factor Model. This chapter summarizes the report and provides conclusions with respect to the accuracy of each method.

SUMMARY

A masonry project in State College, PA, was selected to test the accuracy of three recognized forecasting methods and the Factor Model. The project selected for the case study is a uniquely designed, multistory, steel frame bank building with extensive interior masonry walls.

The different forecasting methods that were selected be used in this study are percent complete, learning curve, standard productivity curve and Factor Model. The percent complete, learning curve and standard productivity curve forecasting methods are based on generalized standards of performance and are widely used in the construction industry. The Factor Model accounts for specific job factors and requires a milestone schedule to develop a forecast.

The first step in forecasting with the Factor Model is to develop a productivity trend curve. This requires several steps which are outlined as follows:

1. Detailed quantity estimate by line item

2. Calculate unit rate for each line item
3. Compute the work-hours and duration of each line item
4. Develop a milestone schedule
5. Develop productivity trend curve based on the milestone schedule and the planned daily work-hours

Once the productivity trend curve has been developed, it is then used as a basis for forecasting the activity.

The productivity trend curve for the Factor Model was compared with the productivity trend curves developed for the other methods. Each curve was widely separated from the other curves in the first third of the activity but converged as the activity neared completion.

Actual progress of the activity was impacted by many different conditions and events. The actual productivity exceeded the estimated productivity by more than 30%. A major cause of the overrun was because the work was done in the winter, and the contractor was required to construct temporary enclosures throughout 75% of the activity's duration. The contractor's planned schedule was revised after the construction of the temporary enclosures.

Disruptions occurred on 39 of 110 work days. Their impact was assessed with the use of indices and accounted for 23% of the work-hour overrun. Principal disruptions were 11 days for weather and 10 days for rework.

Another factor that influenced the productivity was the unique design of the building which required extra care in laying out and construction. Additionally, the masonry work was not subcontracted but

was done with the prime contractor's own work force. Each one of these items increased the uncertainty of the forecasting accuracy.

Weekly forecasts were made for 26 of the activity's 27 week duration. All of the methods produced divergent forecasts throughout the first third of the activity. This was because considerable work-hours were expended constructing temporary enclosures. When the work on the temporary enclosures was finished and masonry work resumed, productivity improved as predicted by the learning curve and standard productivity curve even though more difficult masonry work was being done.

The Factor Model produced a forecast within 4% of the final productivity after only 3% of the work had been completed. If the inefficiencies associated with the temporary enclosures had not occurred it is conceivable that the Factor Model could have given acceptable forecasts for all but the first week.

CONCLUSIONS

The accuracy of each forecasting method improved as the project neared completion. The Factor Model produced a forecast within 4% of the final productivity after only 3% of the work was done. The forecast curve based on the Factor Model closely simulated the actual productivity curve in the early weeks of the activity and would have produced an acceptably accurate forecast (within 10 %) for the entire duration of the activity had it not been for the major disruptions in week 4. The standard productivity curve and learning curve models

produced accurate forecasts because the effect of disruption was so severe that subsequent work performed at a better rate lowered the cumulative productivity average even though harder interior work was being done.

This research did not show that the Factor Model produced more accurate forecasts than the other methods. However, it did show that the different forecasts were equally accurate. Thus, it appears that the Factor Model is a viable alternative to conventional forecasting techniques.

RECOMMENDATIONS

Before the Factor Model can be accepted as a viable forecasting method, additional case studies should be done to determine if it can accurately forecast productivity for a wide range of masonry projects. This should also provide the opportunity to forecast a project during the normal construction season and not during the winter months.

The adjustments used in preparing the trend curve for the Factor Model are principally based on construction with concrete masonry units, additional effort should be spent refining the adjustment factors for construction with brick masonry units.

A major problem encountered was that it was very difficult to quantify the impact of different types of disruptions on the overall progress of the project. Additional research to quantify the impact of disruptions would help in future research to validate the Factor Model.

APPENDIX A

STANDARD CONVERSION FACTORS

Concrete Masonry Unit

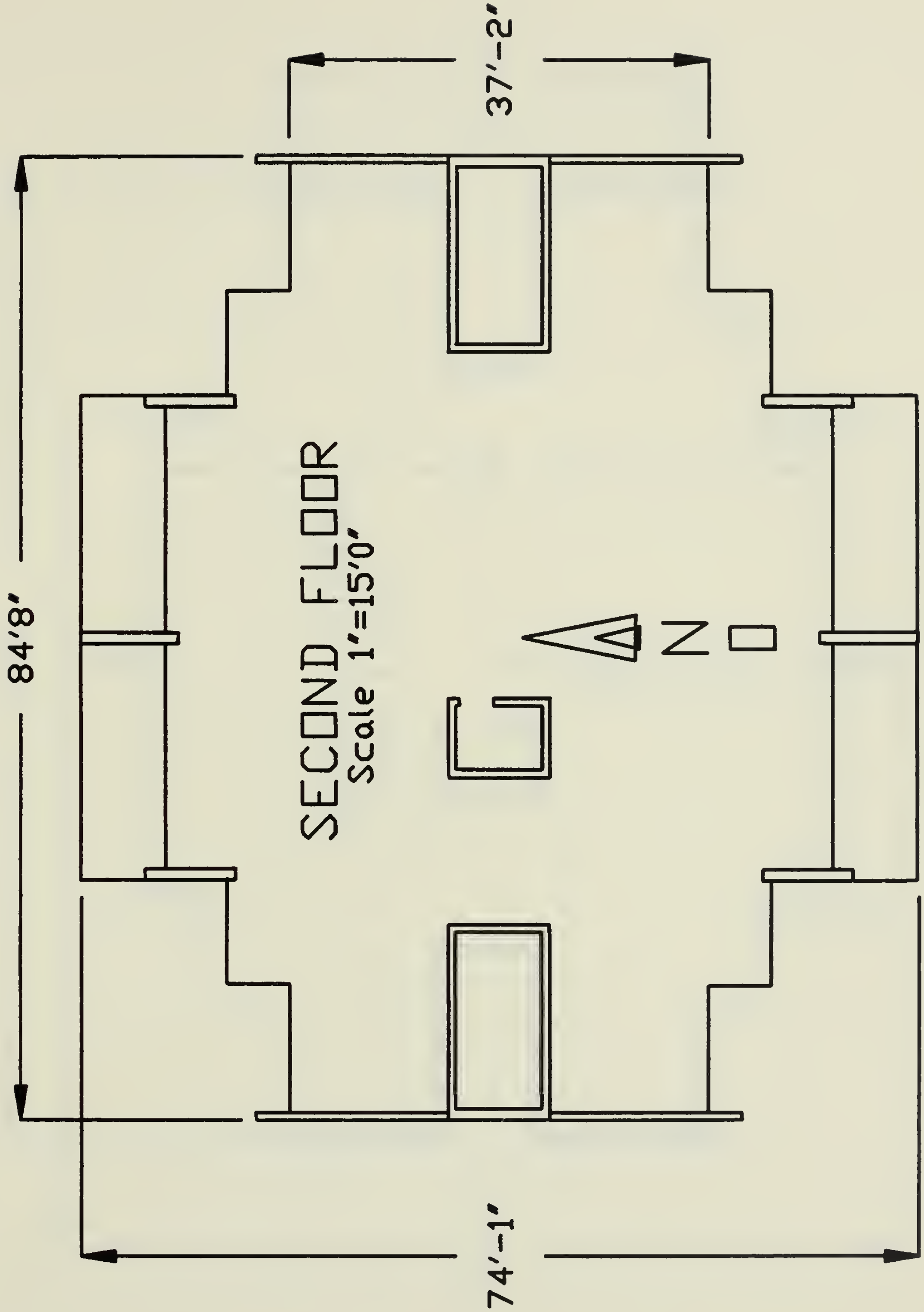
SIZE (LxWxH)	WEIGHT (lbs)	CONVERSION FACTOR
16 x 4 x 8	25.0	0.83
16 x 6 x 8	29.0	0.88
16 x 8 x 8	39.0	1.02
16 x 10 x 8	47.6	1.13
16 x 12 x 8	54.8	1.23

Brick

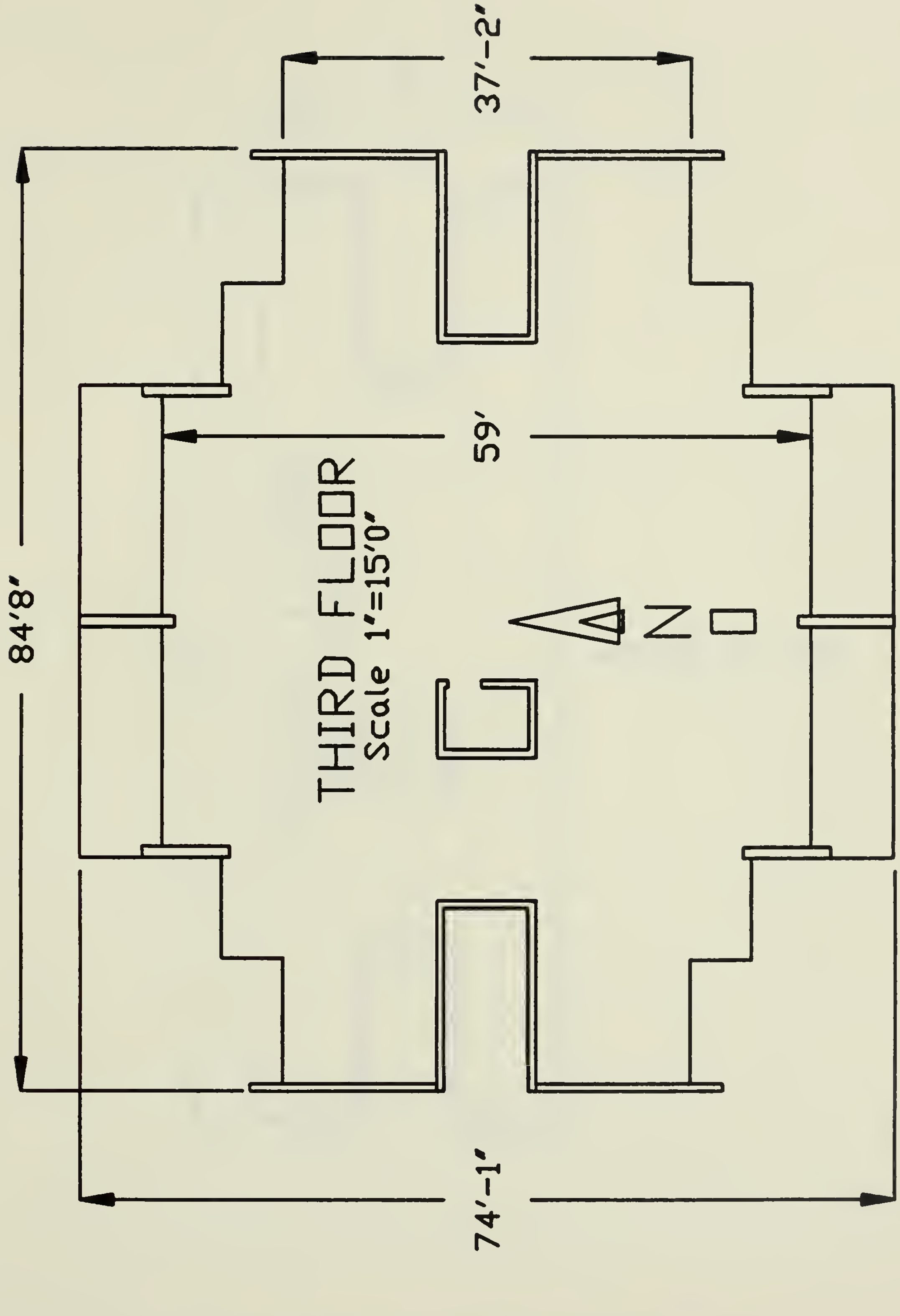
SIZE (LxWxH)	FACE AREA(sq in)	CONVERSION FACTOR
8 x 4 x 3	21.34	1.73
8 x 4 x 2.25	18.00	1.95
8 x 4 x 4	29.00	1.40
12 x 4 x 2	24.00	1.60
12 x 4 x 3	32.00	1.30
12 x 4 x 4	48.00	1.03
16 x 4 x 8	128.00	1.58

APPENDIX B

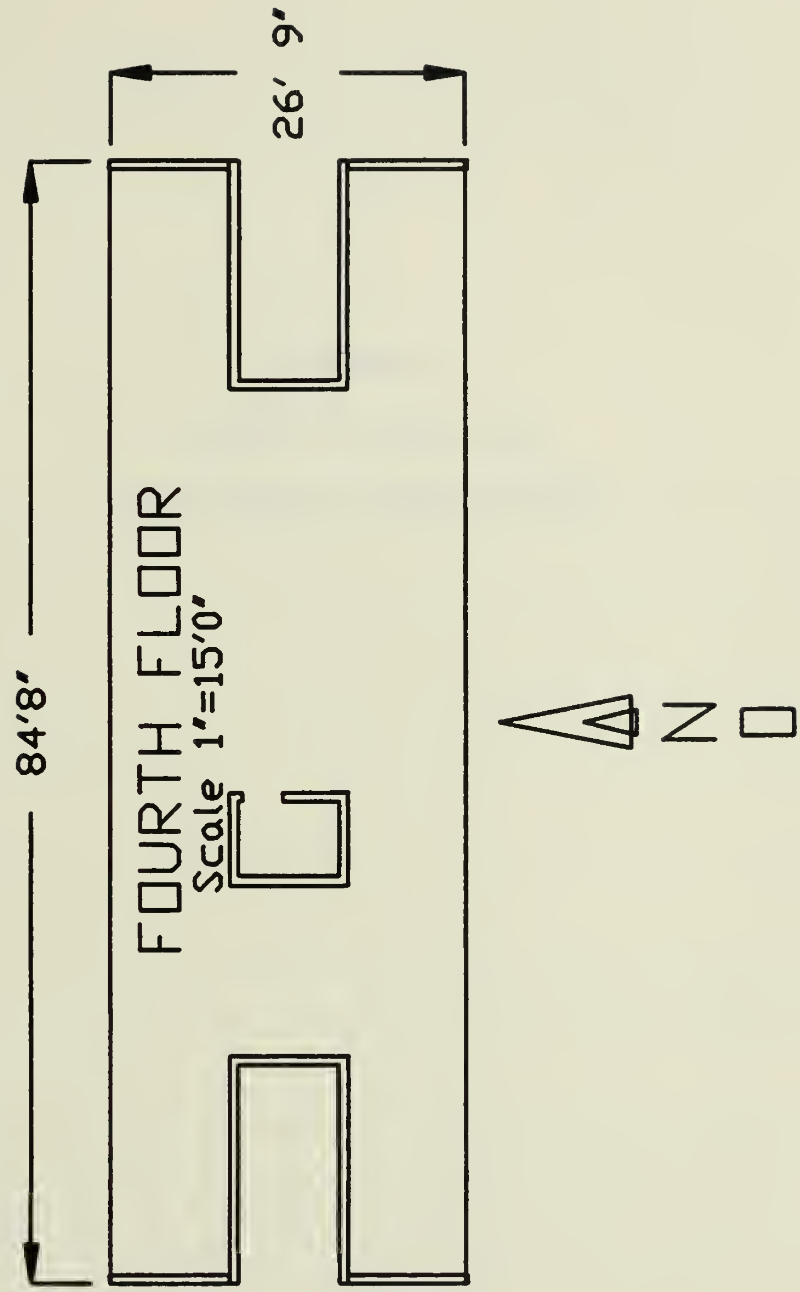
BANK FLOOR PLANS



Second Floor Plan on United Federal Savings Bank



Third Floor Plan on United Federal Savings Bank



Fourth Floor Plan on United Federal Savings Bank

APPENDIX C

CRITERIA FOR WORK TYPE, WORK PHASE AND DESIGN DETAILS

WORK TYPE

Work done over periods of time are to be identified by type of work. A project may progress through several types of work. In general, the type of work will be associated with a phase of work and will remain the same for perhaps several weeks or more.

Masonry

For masonry activities, enter the type of work according to the following:

<u>Code</u>	<u>Description</u>
[1]	First Floor Repetitive - first repetitive floor of a multi-floor structures where the design requirements and floor plan are nearly identical from floor to floor. The work on each floor, including interior and exterior, can be done from the floor slab (overhand), thus requiring little scaffolding. The floor area in not normally that large so material distribution is relatively simple. The crew usually is not dispersed. The ground floor of most multistory buildings has a unique layout and is denoted in the other category. The next floor is the first repetitive floor.
[2]	Remaining Floors Repetitive - other floors in the repetitive structure.
[3]	Brick - work consisting entirely of exterior or interior brick. Material distribution may not be as simple as on repetitive floors, and the crew may be more dispersed. This is typically a building facade.
[4]	Other - structures involving non-repetitive design using brick and block or block only. Walls may be higher than those normally seen in repetitive work. The lack of repetition requires more layout, and work is often done between or around the structural steel or reinforced concrete frame. Typical projects are single or two story facilities like supermarkets, office buildings, recreation centers, and armories. Foundation work and basements and the ground floor (atypical) floor of a repetitive structure are included in this category.

WORK PHASE

Work phase refers to components that can be identified from the construction drawings.

Code Description

[1] Foundations/footings - masonry work generally constructed below the ground slab or floor level that serves strictly as part of the foundation and is not incorporated into a wall. Basement walls are not included in this category. Foundations are usually long courses with few openings. Layout is simple and requires little or no scaffolding or cutting.

[2] Exterior walls - outer walls, including basement walls above the slab on grade. Exterior walls normally have long courses interrupted only by doors, windows or the structural frame. Extensive scaffolding may be required unless the overhand method is used. Layout is minimal.

[3] Interior straight walls - inner walls that are generally longer than 15 ft. with few openings and/or corners. These require little or no scaffolding. Layout time and cutting requirements are minimal.

[4] Interior core walls - inner walls that are generally shorter than 15 ft. or longer walls with numerous openings and/or corners. Elevator shafts and stairwells are included in this category. The work is characterized by considerable cutting and/or layout time. Scaffolding may be needed when working on elevator shafts and stairwells.

[5] Column/ornamental brick - includes masonry on columns or brickwork designed to produce an ornamental or decorative effect by using something other than standard patterns. Layout is more time consuming. Quality control may be more important, and some additional cutting may be required.

[6] Penthouse/roof machine room/parapet - any roof structure that is unique in design from other phases of the project. These structures are generally small and require a proportionately larger amount of layout time. Scaffolding requirements are minimal.

[7] Finish work - includes the dismantling of scaffolding, removal of excess materials, patching, piecemeal work (jobbing), and cleanup activities that are associated with the end of the project. Normally, only the last two or three days of the work are classified as finish work. Few quantities are installed.

DESIGN DETAILS

Design details are specific features of the work that are more detailed than the physical elements. Design details generally reflect a choice or prerogative of the designer and are classified as follows:

Code Description

[0] None - none of the categories listed below apply.

[1] Double wythe - work is dominated by double wythe (leaf) walls.

[2] Triple wythe - work is dominated by triple wythe (leaf) walls.

[3] Straight walls with few corners or doors - a special category of interior straight walls where there are very few doors and openings. This work should be highly productive because there is very little layout time and no detail work.

[4] Irregular walls - walls that require excessive layout time and detail work because there are many short lengths and/or there are numerous openings around doors and windows.

[5] Cutting - excessive cutting and sawing is required because of design details. This may occur if the floor height is not an integer multiple of the block height. It will also occur when masonry units must be integrated with structural steel columns and beams. Here, much detail work is required. Routine cutting around doors and windows is not included.

[6] Corners not 90^0 - includes those days where the work is dominated by laying out non rectangular corners.

[7] Large lintels - covers days when work is dominated by the installation of large lintels that require crane or mechanical assistance.

[8] Falsework support - pertains to work around windows and doors where there are arches requiring temporary supports.

[9] Restricted access - relates to areas on the project that are difficult to reach or where the work area is very confined. This category of work is the result of the design and layout of the project and is set apart from the congestion category on Form 5 which is caused by the contractor assigning too many persons to work in the same area. Restricted access is of design origin.

[10] Stringent quality control requirements - this category covers situations where superior workmanship is required beyond what is normal.

APPENDIX D

USE OF FACTOR MODEL AS AN ESTIMATING TOOL

INTRODUCTION

In developing a forecast using the factor model, it is necessary to estimate the total work-hours required to complete the work. Many manuals and guides have been written to help develop work-hour estimates. One well known manual is "General Construction Estimating Standards" published by Richardson Engineering Services [18]. This chapter compares the ease of use between the factor model approach and Richardson´s Estimating Manual for estimating masonry work-hours.

RICHARDSON´S ESTIMATING MANUAL

To develop an estimate using Richardson´s Estimating Manual the information listed in Table 19 is required. Quantity take-offs are needed for each type of wall and type of finish.

The estimated work-hours required to complete a line item are computed in two steps. A base unit rate for the basic wall section is determined and then adjustments are made for various relevant factors. There are 15 separate items that can result in adjustments to the base rate. Many of these require an additional quantity take-off, for instance the linear feet of corners. A similar but less detailed approach is required for finishes. For example, to compute the exterior C.M.U. walls the following separate measurements need to be made to determine the work-hours:

Table 19. - Information Required by Richardson's Estimating System to Determine Required Work-hours

1. Type of Material
   * Hollow Masonry Units
   * Bricks

2. Base Unit Rate
   a. Type of Walls in Square Feet

* Exterior Foundation	* Interior Foundation
Exterior Basement	Interior Basement
* Exterior Above Grade	* Interior
Firewall	* Column or Piers
Retaining Walls	Fences
Arches	Beams
Misc. Minor Brickwork	* Single-Wythe
* Double-Wythe Cavity	
Double-Wythe Grouted and Reinforced	
* Triple-Wythe Grouted and Reinforced	

(*) denotes items used in preparation of estimate for case study

(cont. on next page)

Table 19. (cont.)

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b. Finishes in Square Feet

- * One Face Covered with Plaster or Wallboard
- One Face Covered with Face Brick
- Both Faces Covered with Plaster or Wall Board
- * Both Faces Exposed

3. Adjustments

a. Additive Items Measured in Square Feet

* Height Above 12 Feet	Stacked Bond
* Type of Joint	Curved Walls
Chases and Reveals	Design Patterns

b. Additive Items Measured in Linear Feet

* Control Joints	Raked or V Joints
* Curtain Wall Perimeter	* Corners
* Intersections	* Mitred Corners
* Perimeter of all Openings	
Top Bearing Surface for Bearing Wall	

c. Additive Items Measured by Piece

- * Cut Brick for Conduit, Pipe and Structural Steel

(*) denotes items used in preparation of estimate for case study

base unit rate	0.773 wh/block
convert block to square foot	1125 block/sq ft
interior above grade cover with wallboard	deduct 10% from work-hours
height above 12 ft.	add 0.01 wh/sq ft
curtain walls	add 0.16 wh/lineal foot of perimeter
corners	add 0.16 wh/lineal foot of vertical distance

A total of four different quantity take-offs are required to complete the estimate.

The system is very extensive and can seem overwhelming to the first time user. A computer program was written in 1983 by Tawil at The Pennsylvania State University to assist in completing an estimate using the Richardson system [19], however, the program is no longer available.

FACTOR MODEL

An estimate is prepared with the factor model is done by determining the square foot of wall area, minus openings, of the various wall types shown in Table 6. This quantity is then multiplied by the unit rate calculated using Equation 10 and the adjustments listed in Table 6 as outlined in Chapter 3. No additional quantity take-off is required. There is one base unit rate and a maximum of five adjustment factors. However, the factor model does require that quantities be

converted to the standard unit.

COMPARISON OF THE METHODS

The Richardson estimating system was used to develop a work-hour estimate for the case study. A total of 18 line items were required for the factor model and 24 were required by the Richardson system. The work-hour estimate was compared with the total work-hour estimate obtained using the factor model approach. The results are in Table 20.

Table 20. - Comparison of Estimates

Estimate Method	Total Work-hours	Unit Rate
Richardson	6,783	0.179
Factor Model	6,813	0.181
Actual	8,881	0.237

As can be seen the difference between the two methods is negligible. However, the factor model required about half the time to compute and summarize. For an experienced user the time difference should be even greater.

SUMMARY

A comparison was made between the Richardson estimating system and

the factor model approach for estimating masonry work-hours. Both methods required the consideration of approximately the same amount of factors and produced essentially the same work-hour estimate. The Richardson system required four different measurements for a typical wall section while the factor model only required one measurement. The factor model approach took roughly half the time.

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